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Two-year Growth and Mortality of Sub-Canopy Baldcypress (Taxodium distichum [L.] Rich.) in Artificial Canopy Gaps in a North Carolina Swamp

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TWO-YEAR GROWTH AND MORTALITY OF SUB-CANOPY BALDCYPRESS (*Taxodium distichum* [L.] Rich.) RELEASED IN ARTIFICIAL CANOPY GAPS IN A NORTH CAROLINA SWAMP

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Baldcypress (*Taxodium distichum L.*) –tupelo (*Nyssa spp.*) swamp forests are a major component of the total area of southeastern U.S. forested wetlands, which provide valuable ecosystem services related to water quality, stormwater catchment, and wildlife habitat. Historically, baldcypress has also been an important source of wood products, and clearcutting the principal method of harvesting and regenerating the species. However, anthropogenic alterations to flows of many rivers and the associated flood patterns of alluvial wetlands have prevented the establishment of new baldcypress cohorts in many swamps. Regular, extended growing season flooding could prevent germination and/or establishment of baldcypress seedlings if clearcutting were to occur. Where advanced baldcypress regeneration does occur, its ability to respond to release via overstory cutting or removal remains unknown, especially for long-suppressed saplings.

In this study, I tested sub-canopy baldcypress sapling response to release in twelve 456 m^2 artificial canopy gaps created through girdling and injection of all canopy trees in a water tupelo-dominated 'backswamp' of the lower Roanoke River floodplain, eastern North Carolina. Leaf area index and diffuse non-interceptance were measured for all treated and untreated plots, and diameter growth, basal area growth, and mortality of clustered saplings ranging from <1 – 24 cm dbh were recorded over two post-treatment years. Additionally, subsets of saplings were cut and slabs removed for aging.

Saplings ranged in age from 12 – 38 years and most likely established during short periods of minimal growing-season flooding. Sub-canopy light levels averaged 1.3 +/- .4% in untreated plots and 16.9 +/- 6.5% in treated plots. Saplings responded to treatment with strong radial growth, adding nearly eight times as much basal area and diameter growth as saplings beneath intact canopy over two years. Mortality levels in both groups were quite high (9-11%) in the first post-treatment year, but by year two

death in treated plots had dropped to 2.5%. Mortality was inversely related to plot initial quadratic mean diameter of plots.

The study confirms the ability of sub-canopy baldcypress to respond well to release, and provides justification of a useful tool for the management of the species in uneven-aged stands.

CHAPTER 1 - INTRODUCTION

The southeastern U. S. hosts an array of forested ecosystems dominated by a variety of major tree species and exhibiting a suite of successional states driven by a complex mixture of disturbance types and biotic and abiotic factors and processes. Forested wetlands, wetlands dominated by trees, are a common and important class of forests in the Southeast. Most are classed as Palustrine wetlands except those in tidal zones, which fall into Estuarine wetland systems (Shepard et al. 1998).

Among the most widespread and valuable forested wetland types in the southeastern U.S. are baldcypress-tupelo swamps, named for the tree species which generally dominate their canopy layer – baldcypress (*Taxodium distichum* (L.) Rich.), water tupelo (*Nyssa aquatica* L.), and/or swamp tupelo (*Nyssa biflora* Walter). Baldcypress-tupelo forests occur throughout the zone of overlap in the ranges of all three species (generally the southeastern U.S. to southern Illinois in the NW, northern Virginia in the NE, northern FL in the SE, and southeast TX in the SW; Wilhite and Toliver 1990). Baldcypress' range is somewhat larger than that of water tupelo, occurring further south into south Florida and further north into Delaware. Within the zone of overlap for these three species, differences in tolerance to flooding, preferred soil types, processes acting on seed dispersal and germination, and within-stand competition all likely influence the relative dominance of one species over another, and forests exist across a gradient from those composed solely of one or both tupelos, mixtures of tupelo and baldcypress, to those composed entirely of baldcypress.

Baldcypress-tupelo forests generally occur in areas generally subject to above-ground flooding for parts or all of the year (Penfound 1952, Conner and Buford 1998). Floodplains of most major rivers (alluvial floodplains) in the southeastern U.S. do, or once did, support large tracts of baldcypress-tupelo forest which are, or were, flooded via

overbank flooding during periods of high flow. Baldcypress-tupelo forests also occur as isolated depressional wetlands.

The composition and dynamics of these forests are heavily influenced by hydrology. Very small changes in elevation (a few cm) can cause significant changes in length and depth of flooding, soil characteristics, and plant communities (Conner and Buford 1998). Hydrology drives or influences many important processes within these forests – biogeochemistry and soil development, sedimentation, drought and flood disturbance, seed dispersal, and germination conditions. Baldcypress-tupelo forests usually occur on moderately to strongly acidic soils ranging from mucks and clays to silts and sands (Wilhite and Toliver 1990, Conner and Buford 1998) that are relatively high in nutrients and organic matter (Sharitz and Mitsch 1993).

Forested Wetland Trends and Importance

When European settlers first arrived in the southeastern U.S., massive amounts of baldcypress-tupelo swamps and many other forested wetland types existed. It is estimated that in the Louisiana delta alone, some 35 million m^3 of baldcypress timber was present (Kerr 1981), most of which could be considered old-growth.

Approximately half of all wetlands in the United States were lost between 1600-1985 (Lockaby 2009), mostly due to conversion to agriculture. In 1996, approximately 14.05 million ha of forested wetlands (all types) occurred in the southeastern U.S., with 91% being riparian (Ainslie 2002). In the early 1980's, there were between 1.2 and 2 million ha of second-growth baldcypress-tupelo forest across the South (Williston et al. 1980, Conner and Toliver 1990). More recent estimates show that the 13-state southeastern region contains over 1.3 million ha, with over 55% located in LA and FL (Greis and Brown 2008). Estimates of major and minor alluvial floodplain forest area, which would include the majority of existing baldcypress-tupelo forest, amount to

roughly 12.77 million ha (31.8 million ac; Ainslie 2002).

Between 1986 and 1997, 90% of forested wetland loss in the Southeast was due to conversion to another wetland or aquatic habitat type. Roughly 48,000 ha were converted to urban and rural development, 45,000 ha were converted to agricultural use, and about 40,000 ha were transformed for intensive silviculture (Ainslie 2002). A total of 1.405 million ha (roughly 3.5% of all forested wetlands) were converted during this period. Today, urbanization is the primary cause of wetland loss in the southeastern U.S. (Faulkner 2004, Hansen 2006).

Values of Baldcypress-Tupelo Forests and Forested Wetlands

Though forested wetlands function as part of the landscape with or without humans, many of their functions are quite valuable to society (Mitsch and Goselink 2000). It must be noted that the value provided by a forested wetland stems from the functionality of the wetland itself, its location and extent, and the human population pressure exhibited on it (Mitsch and Gosselink 2000). Many forested wetlands are coupled to trophic food webs which support aquatic and wetland species important at a commercial scale (Walbridge 1993, Harris and Gosselink 1990). Forested wetlands also protect water quality by transforming inorganic nutrients, such as PO_4^{3-} and NO_3, to their organic forms, which helps prevent eutrophication and disruption of downstream aquatic food webs (Walbridge 1993, Duryea and Hermansen 1997). In this same capacity, both baldcypress and pondcypress swamps can remove P and N from secondarily treated wasterwater (Ewel 1990), and this usually leads to increased growth rates of trees in the swamp, which can be sustained for decades (Nessel et al. 1982, Brown and Van Peer 1989, Hesse et al. 1998).

Forested wetlands also provide flood control and groundwater recharge. While depressional wetlands have been shown to provide flood storage and groundwater

recharge capabilities (Ewel 1990, Duryea and Hermansen 1997), riparian forests may be less efficient in these functions (Walbridge 1993). Riparian wetlands usually provide sediment retention, detrital production, flood control, and corridors for migrating wildlife (Mitsch and Gosselink 2000).

Though baldcypress-tupelo forests do not support any fauna completely unique to that ecosystem (Harris and Vickers 1984), they are extremely important because of their extent, normal proximity to rivers or other large bodies of water, and structural characteristics. Baldcypress-tupelo forests provide important habitat for Rafinesque's big-eared bat (*Corynorhinus rafinesquii*) and the southeastern bat (*Myotis austroriparius*), both federal species of concern (Faulkner et al. 2009). Rafinesque's big-eared bat frequently uses hollow water tupelo trees in very mature baldcypress-tupelo forests for roosting, such as in the Broadneck Swamp, NC (Lance et al. 2001, Gooding and Langford 2004). Tree dens are commonly used by black bears and other mammals in areas that are regularly flooded (Hightower et al. 2002). Wakeley and Roberts (1996) found that heavily flooded baldcypress-tupelo forests in Arkansas supported denser populations of breeding birds than drier forest types nearby, though overall bird richness was lower. Specifically, chimney swifts (*Chaetura pelagica*), prothonotary warblers (*Protonotaria citrea*), and great crested flycatchers (*Myiarchus crinitus*), all cavity nesters, were especially abundant in these swamps. The lower Roanoke River, NC floodplain hosts 214 bird species, 88 of which are known to nest there, including 44 tropical migrants, many of which are thriving in the region while populations are declining across other parts of their range (Pearsall et al. 2005). Historically, water tupelo has been used as a nectar tree in apiculture because of the prized honey produced (Stallins 2010). Baldcypress-tupelo swamps also provide recreational activities similar to those many other forest and wetland types provide - sport fishing and hunting, hiking, boating, nature study, and photography (Hickman 1990).

In the past, baldcypress-tupelo swamps were valued for the volume and quality of timber within them. Baldcypress has been extensively logged since European settlers arrived. Old-growth baldcypress heartwood is decay-resistant, though second-growth non-heartwood is not nearly so (Choong et al. 1986). Harvesting of baldcypress reached a peak in 1913, when more than 2.36 million m^3 were cut (Williston et al. 1980). By 1954, production was down to 566,000 m^3, and today is below that (Williston et al. 1980). Water tupelo was cut far less during peak periods of harvest, partially because of lack of decay resistance and also because its form was not nearly as desirable as tall, straight, limb-free baldcypress.

Today, baldcypress is most often used for decking, fencing, interior paneling, or garden mulch (Brandt and Ewel 1989). In the late 1990's 99,000 m^3 of baldcypress was harvested annually in Florida, with about 53% cut into lumber and 47% used for landscape mulch (Duryea and Hermansen 1997). Approximately 60% of all landscape mulch sold in Florida is from baldcypress (Duryea 2001). Clearcutting second-growth stands of baldcypress for use in mulch has caused concern in some areas over sustainability of the baldcypress resource in recent years (Chambers et al. 2005), but clearcutting for this purpose is fundamentally no different than clearcutting a stand for sawtimber, given regeneration is ensured. In many places where harvesting has been done for various purposes, regeneration has not occurred naturally, and forests are converting to other forest types, to marsh, or to open water (Keim et al. 2006). To date, clearcutting has been, and will likely remain, the most efficient way of regenerating baldcypress stands because of the nature of the species' regeneration ecology.

Baldcypress Growth and Regeneration Ecology

Shade Tolerance

Light availability is of overriding importance to growth of sub-canopy saplings of various species in eastern deciduous hardwood forests (Ricard et al. 2003), and shade tolerance has been extensively studied for many commercially exploited tree species. Light requirements of baldcypress have only been examined at very early life history stages (*i.e*. seedlings one to a few years old). At these ages, baldcypress may vary widely in survival and growth depending on local microsite conditions such as hydroperiod, available light, and soil fertility (Souther and Shaffer 2000). In terms of light, Demaree (1932) showed that seeds were able to germinate in heavy shade, but did not survive into the second growing season. Browder et al. (1974) found that seedlings' increase in total biomass was greatest at 80% of full sun, but height growth was greatest at just 32% full sun. Neufield (1983) also found that total biomass production in young seedlings was highest at light levels slightly less than full sun, but that height growth was optimized at 25% full sun. However, Souther and Shaffer (2000) found that growth of newly germinated seedlings was depressed under low light conditions (25% of full sun). In that study, seedling growth was generally best at 80% full sun, regardless of the period of inundation. One-year-old seedlings were affected less by differing light levels and grew roughly 30 cm over the year. They were, however, more sensitive to soil conditions, and fertilization caused a significant increase in height growth across all light regimes.

Thus, it seems that young baldcypress seedlings are able to survive and grow well, if not optimally, in low light conditions. However, no studies have continued to monitor survival and/or growth of these seedlings into later age classes, especially in a natural environment. It is unknown whether baldcypress is "shade tolerant" in the sense that it is able to survive and subsist or slowly grow in low light conditions for long

periods of time and subsequently take advantage of gaps in the canopy which would provide high light and the ability for the tree to suddenly increase growth. If so, this would mean the species utilizes two dominance strategies in terms of light – one akin to shade tolerant upland species like sugar maple (*Acer saccharum* Marsh.) and American beech (*Fagus grandifolia* Ehrh., see Barnes et al. 1988), and one more akin to pioneer species such as cottonwood (*Populus deltoids* Marsh.) or many pines (*Pinus spp*.), which colonize disturbed, high-light environments and develop quickly in even-aged stands.

In general, many tree species are able to germinate and initially survive in the understory of mature forest canopies, but most are unable to survive and grow over decades under such conditions (Barnes et al. 1988). Studies of various species in different ecosystems have shown that survival in the understory is potentially dependent on a range of different physiological responses to environmental conditions there. Ultimately, survival depends on the ability of a plant to photosynthesize enough to counterbalance respiration losses. Whether this is possible in the understory depends on factors such as 1) maintaining adequate leaf area, (2) photosynthesizing more efficiently per unit leaf area, (3) maintaining lower rates of respiration per unit leaf area, (4) producing more plant tissue per unit water lost to transpiration, and/or (5) absorbing water more efficiently (Barnes et al. 1988).

"Shade intolerant" species in many ecosystems have actually been shown to die in understory environments due to competition for water rather than light. This is often due to the nature of root growth of these species. Loblolly pine (*Pinus taeda* L.), for example, will survive for several years in an understory environment but cannot produce enough photosynthate to develop a root system capable of reaching deeper soil layers. When even moderate drought strikes, these individuals are no longer able to compete (Barnes et al. 1988) and usually die. In many open forest types – ponderosa pine (*Pinus ponderosa* C.

Lawson) forests of the American west, for example - sunlight is ample but soil water drives survival of seedlings and saplings (Barnes et al. 1988).

Some studies have shown that the near-universal tendency of the replacement of shade intolerant species in the canopy by shade tolerant ones may not apply in somewhat regularly flooded forests because of a tradeoff between shade tolerance and flood tolerance (Battaglia and Sharitz 2006, Mann et al. 2008). In other words, those species able to survive and grow in the understory of floodplain forests are less likely to be flood tolerant and thus less likely to eventually succeed into the canopy. This is certainly true in deeply flooded baldcypress-tupelo forests, in which very few species exhibit both the shade and flood tolerance necessary to survive and grow in the understory. Baldcypress itself is, of course, extremely flood tolerant at later life history stages and is classically considered intermediate in shade tolerance (Wilhite and Toliver 1990).

Though natural regeneration of baldcypress in swamps across the southeastern U.S. is now rare (Myers et al. 1995, Conner et al. 1986, Souther and Shaffer 2000), often due to anthropogenic hydrologic alteration (Keim et al. 2006, Faulkner et al. 2009), there are occasional exceptions (Conner and Muller 1989, Keeland and Conner 1999). Due to its germination requirements, baldcypress tends to be found in even-aged stands (Shankman 1993) and is able to survive and grow slowly in low-light conditions for many years (*sensu* Conner and Muller 1989). However, growth appears to stagnate when saplings growing in relatively dense sub-canopy stands reach midstory height levels. As baldcypress in high-light conditions is able to maintain impressive volume growth in very dense stands well into older ages (Wilhite and Toliver 1990, Goelz 1995), it seems that a combination of low light and high basal area (intense competition) may interact over time to produce a stagnation in growth and an increase in mortality.

Is Baldcypress Adapted to Take Advantage of Gaps?

Trees in an understory condition, unless extremely shade tolerant, are generally unable to access resources at a level required for optimal growth, and often must adapt physiologically to deal with these conditions. Shade tolerance is a gradient bounded by two extremes in the nature of growth in low-light environments. On one extreme, sub-canopy trees are able to grow slowly and consistently but do not respond well to canopy openings, or gaps (Canham 1989). On the other extreme, sub-canopy trees are able to survive or persist for long periods but grow very little or not at all until the formation of an overhead gap, to which they respond with drastically increased growth (Canham 1989). It is unclear where along this gradient baldcypress falls. In general, there seems to be a tradeoff between a species' ability to grow at high light and its ability to survive at low light (Canham 1989, Pacala et al. 1994, Gravel et al. 2010). However, Gravel et al. (2010) found that the high-light growth/low-light survival tradeoff, though perhaps ubiquitous among forest tree species, is not likely to be an important process in the stable coexistence of several tree species. In southeastern U.S. swamps, the coexistence of water tupelo and baldcypress likely has less to do with long-term species-specific shade tolerances and more to do with the interaction between hydrologic conditions and seed sources following major disturbance. Nevertheless, given the longevity of baldcypress as an adult and its ability, though rare, to regenerate beneath a mature canopy, growth and light requirements of sub-canopy saplings are important to long-term swamp forest dynamics.

As noted previously, baldcypress is able to survive and grow slowly for many years beneath a canopy, but its ability to respond efficiently to gap formation at juvenile life history stages has not yet been tested. It is quite possible that survival and growth in both shade and new gaps changes as an individual grows older and spends more time in

an understory environment. Canham (1989) notes that "the ability to tolerate shade may decline as an individual grows if ratios of photosynthetic to non-photosynthetic tissues decline as height and crown size increase… prolonged suppression or slow growth with a marginal net carbon balance should increase the chances that a sapling will succumb to pathogens, defoliation, or episodic drought." Length of time in an understory condition may also increase the lag time required for an individual to respond to an overhead gap (Poulson and Platt 1989). These effects can be summarized as "suppression effects."

The notion that "stagnation" (suppression effects) may cause delayed response or completely prevent response to overhead gap formation has been researched for only a handful of species. Wright et al. (2000), studying 11 different species in northern British Columbia, found that periods of suppression did not cause shade-tolerant species to lose their ability to respond to release following partial cutting of the overstory. Less shade tolerant species showed a lag in response to release, particularly if they had been suppressed (Wright et al. 2000). In that study, shade tolerance was assessed by the light level associated with a sapling mortality of 10% over 3 years, and these levels ranged from 6 – 37%. Ferguson and Adams (1980) showed that younger grand fir (*Abies grandis* (Douglas x D. Don) Lindl.) were able to adjust quickly to the sudden change in environment caused by overstory removal, while older trees did respond but took longer to do so. Though baldcypress classed as "suppressed" did respond to increased light from thinning in one study (Dicke and Toliver 1988), "suppressed" trees showed the weakest growth, and these trees were likely of the same even-aged cohort as the dominants and co-dominants of that stand.

Considering the low light levels and length of time in an understory environment for saplings, is growth in either gaps or non-gaps affected by the density of a cluster? Would a sapling released alone or in a sparse cluster beneath a gap grow appreciably more than saplings released in a dense cluster? As noted above, in high-light

environments, baldcypress is able to grow significantly in volume in very dense stands well into maturity (Wilhite and Toliver 1990, Goelz 1995). However, thinning studies have shown that the species is sensitive to intraspecific competition in even-aged stands and responds well to increased resources from thinning. Dicke and Toliver (1988) found that dominant and codominant baldcypress stems thinned to various basal areas increased diameter growth between 38 and 85% over three years.

Ferguson and Adams (1980) note that 30% of the released grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.) in northern Idaho became suppressed again following initial increases in growth. The probability of this happening 10 years after release was correlated with slow growth before the release, which, in absolute terms, is most likely to be exhibited by relatively smaller saplings initially. This process is also likely to occur among sub-canopy stands of baldcypress released in gaps, and, because only so many adult trees will be able to coexist in the gap area in the future, it is important to understand growth of the largest sub-canopy saplings relative to gap sapling growth as a whole.

Hydrologic Effects on Growth of Seedlings and Saplings

Neither baldcyprees (Demaree 1932) nor water tupelo (Huenneke and Sharitz 1990) can germinate in standing water, and both require short periods of drawdown to germinate and grow tall enough to prevent extensive overtopping by floodwaters during subsequent years (Souther and Shaffer 2000). Even though variations in microtopography exist in the backswamps of most floodplains, these areas are generally inundated to depths that flood most available surface area during a given year. Thus, appropriate periods of growing season drawdown often lead to mass establishment of a single cohort of baldcypress and/or water tupelo seedlings (*e.g.* Keeland and Conner 1999). As noted above, baldcypress may germinate and grow in shade, but natural uneven-aged stands are

rare (but see Keeland and Young 1997), likely because of interaction between shade-depressed growth, regular flooding, and herbivory (Keeland and Young 1997). Once seedlings do establish and grow to heights taller than regular flooding, relatively little is known about hydrology's effects on their continued growth.

Though baldcypress is quite tolerant of flooding in terms of survival, deep growing season flooding has been shown to be associated with decreased radial growth in some studies and increased radial growth in others. Dicke and Toliver (1990) found no significant differences in relative growth for saplings under 25 cm in diameter between continuously flooded and seasonally flooded sites in Louisiana. Keeland and Sharitz (1995) found that sub-canopy baldcypress grew consistently more at permanently flooded sites compared to periodically flooded ones, but suggest this may have been due to higher light levels at those sites. It is unclear to what degree regular, extensive, and deep early growing season flooding interacts with low light conditions to enhance stress and mortality for saplings. Barnes et al. (1988) note that only in forests where light levels at the forest floor are less than 2% is light a single limiting factor to understory survival. Released seedlings and saplings growing in older gaps might provide an indication of the ability of baldcypress to respond to light within a potentially stressful hydrologic regime.

Gap Light Dynamics

The photosynthetically active radiation (PAR) available to sub-canopy plants at any point in time is a function of many variables, including the time of day, season, latitude, slope, aspect, and height and density of the canopy. In many eastern temperate forests, an average of 1-2% full sun is normal at sub-canopy strata (Canham et al. 1990). In studying the effects of canopy gaps, it is important to understand the spatial and temporal differences in light within and around an individual gap in relation to trees potentially receiving light from it. Changes in the sun's path through the seasons leads to

differences in the amount of direct radiation received at any point in or around a gap (Canham et al. 1990). Consequently, instantaneous measurements of PAR cannot provide very useful indices of seasonally integrated light levels in gaps, which are necessary to quantitatively understand the light resources available to trees over the entire growing season (Canham et al. 1990).

A small, single tree gap of 75-100 m^2 may increase PAR by an average of 1-2% in the gap itself and to distances 1-10 m away. This is double the normal light levels available beneath typical closed canopy forests, and is enough to substantially increase growth rates in some shade tolerant species (Canham et al. 1990). However, the duration of high light levels from direct radiation via even large canopy gaps is relatively brief. In a southern hardwood forest of 25 m height, a gap of 500 m^2 is predicted to receive direct overhead sunlight for only about 2.5-3 hrs (Canham et al. 1990). Though trees can clearly utilize "filtered" sunlight, gaps put two limitations on an individuals' adaptation to high light. First, this brief duration of high light provides only a limited time of high potential carbon gain to make up for synthesis and maintenance costs of adaptations to high light (Canham and Marks 1985). Second, at the level of whole plants, many of the architectural responses to high light are the most effective when sunlight is received across a wide range of angles (Canham et al. 1990).

Thus, there is a fundamental difference between releasing a sapling in the middle of a very large "gap," such as a clearcut, in which it essentially receives direct light at all times and a true small gap of even somewhat sizeable proportions. Given baldcypress seedlings' propensity to produce more biomass at light levels slightly less than full sun and their tendency to grow most in height in even lower light levels, releasing older saplings in relatively small gaps should lead to the most efficient overall growth response. Until direct comparisons of growth in gaps vs. larger clearcuts are undertaken, this can only be speculated.

STUDY AREA

This study was conducted in the Broadneck Swamp tract (Fig. 1-1) of the Roanoke River National Wildlife Refuge within the floodplain of the lower Roanoke River between the small town of Hamilton, NC and Williamston, NC. The Roanoke River is considered an alluvial, or "brown water river," as it originates in the mountains of southwestern Virginia and carries a heavy clay sediment load originally derived from erosion of mountain and Piedmont soils (Pearsall et al. 2005). The Roanoke empties into Albemarle Sound approximately 60 river km downstream of the study site. The river is not tidally influenced at the point where the study occurred.

The 25,035 km^2 (9,666 mi^2) Roanoke River watershed lies in both North Carolina and Virginia (NC Division of Water Quality 2002) and is largely rural. In its North Carolina section, the watershed is roughly 60% forested while 22% is cultivated crop land and 6% is developed (total population of 335,194) with a mean population density of 247.74 people/km^2 (NC Division of Water Quality 2002).

The lower section of the watershed supports some of the largest remaining expanses of contiguous tracts of floodplain forest on the eastern seaboard of the United States (Townsend 2001). The "lower Roanoke River" is defined as the stretch of river downstream of the fall line – the geologic point at which the continental bedrock of the interior Piedmont descends to a coastal plain of Tertiary and Cretaceous sediments (Tinkle 1959). The fall line along the Roanoke River occurs near Weldon, NC near the three largest dams on the river.

The Roanoke River National Wildlife Refuge, owned and managed by the U.S. Fish and Wildlife Service, exists in five large, disjunctive tracts mostly along the north side of the lower Roanoke River west of its junction with the Albemarle Sound. The furthest west of these tracts is the Broadneck Swamp tract, containing some 405 ha of floodplain forest near Hamilton, NC.

The study site is located in the "backswamp" of the Broadneck swamp, the lowest area of the floodplain which usually floods the most frequently and to the highest depths (Hodges 1994). Backswamps are typically removed from the river itself, often separated by high levees immediately adjacent to the river and one or more terraces of slightly lower elevation (Hodges 1994). Smith (2007) noted a difference of 2.22 m between average elevations of levees adjacent to the Apalachicola River (in Calhoun County, FL) and the "back sloughs," another name for backswamp, though such elevational differences can vary widely among floodplains. Smith (1996) found that water tupelo/baldcypress communities along the Cache River in AR were only 143 ± 97 m from the channel, and that less frequently flooded bottomland hardwood communities further from the channel were only 1 – 1.6 m higher in elevation.

Lower Roanoke River Hydrology and the Influence of Dams

The long-term (since 1913) mean discharge of the Roanoke River at the Roanoke Rapids Dam (approximately 120 river km upstream of the study site) is roughly 241 m^3/sec. (Pearsall et al. 2005), putting it among the largest rivers of the Atlantic Coastal Plain. Historically, large rain events have caused 1-day maximum flows of 2000 – 2200 m^3/sec. However, dams have affected flows of the Roanoke River and therefore flood patterns in adjacent floodplains (Richter et al. 1996). Dams and reservoirs have tremendous effects on rivers and associated wetlands by altering the flow of water, sediment, nutrients, energy, and biota in these systems (Palta et al. 2003, Graf 2006). Very few large rivers in North America remain undammed (Graf 2006). The Roanoke River is no exception, with eight dams regulating flow before it crosses the fall line (Pearsall et al. 2005). In terms of flow alteration, the three most important dams are the John H. Kerr Dam (the largest, completed in 1953), the Roanoke Rapids Dam (the furthest downstream; completed in 1955), and the Gaston Dam (between the two;

completed in 1963) (Richter et al. 1996). All three dams were built for the combined purposes of hydroelectric power generation and flood control to benefit agriculture and development downstream (Pearsall et al. 2005), and all three are relatively close to each other along the middle reaches of the river.

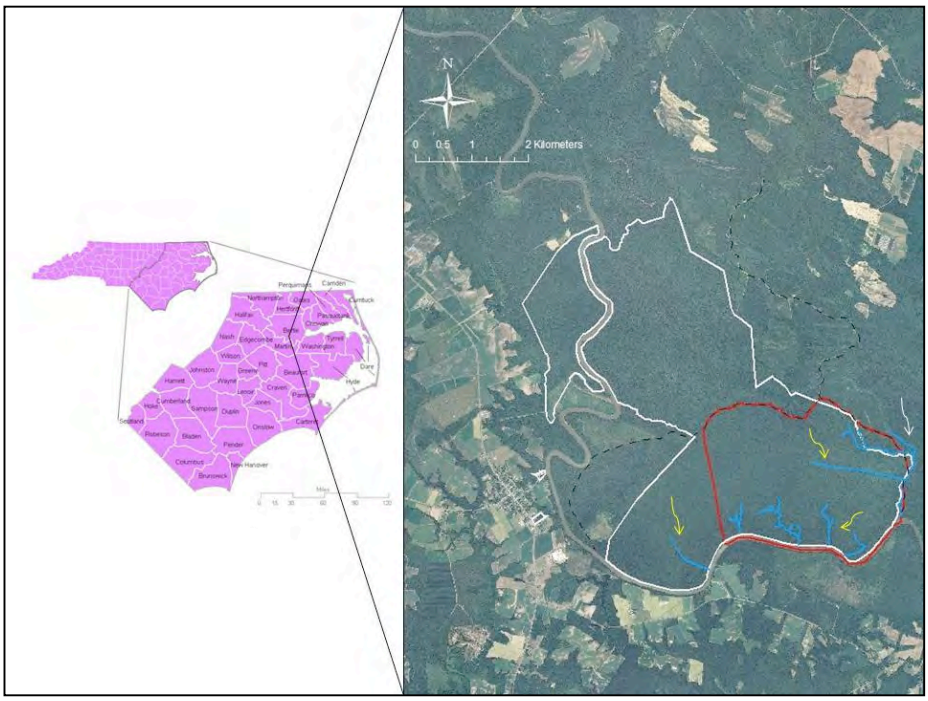

Figure 1-1: The Broadneck Swamp tract (outlined in white) along the Roanoke River near Hamilton, NC (the small town on the left side of the photo). The study site is outlined in red, bordered to the north by a small access road (black dashed line), to the south by the river, to the east by Black Gut (all major canals/inlets in blue), and to the west by an arbitrarily chosen cut-off. The yellow arrows denote the man-made inlet canals that have altered local hydrology of the study site for many years. The white arrow denotes Black Gut, a relatively large natural tributary which reverses flow during high water and is the primary vector for backswamp flooding now that man-made inlet canals have been sealed.

Kerr Dam is the most influential in terms of downstream flows because Gaston Dam is operated as run-of-Kerr, meaning it passes Kerr releases without causing reservoir fluctuations exceeding +/- 15 cm, and Roanoke Rapids Dam is operated as run-of-Gaston (Pearsall et al. 2005). However, because Roanoke Rapids is the furthest downstream, it is mandated by the Federal Energy Regulatory Commission (FERC) to

maintain minimum releases which change seasonally depending on needs of endangered species in the lower Roanoke. These minimums are typically between 28 and 47 m^3/sec (Pearsall et al. 2005).

Despite a current (since 2000) attempt to design an adaptive management plan to mitigate the impacts of regulated flows associated with operation of the three dams, the dams have, since their construction in the mid-20th century, caused severe changes to flow patterns in relation to pre-dam periods. The U.S. Geological Survey has collected daily streamflow measurements just below the Roanoke Rapids dam since 1913, which has allowed a quantitative assessment of these changes (Richter et al. 1996) as well as both 2-D flow and 3-D flood models of flood patterns on various areas of the Roanoke River floodplain downstream (Pearsall et al. 2005).

The most notable hydrologic changes have been a smoothing of streamflows, with reduced variation of winter and summer monthly mean flows, high and low pulse durations, and the frequency and rate of hydrograph rises and falls (Richter et al. 1996). Critical flood pulses (Johnson et al. 1995, Richter et al. 1997, Middleton 1999)– those large, brief periods of high flow which lead to deep but short floods on the floodplain and are associated with nutrient and groundwater replenishment (Brown 1981) – have been replaced by lower flows sustained over longer periods (Pearsall et al. 2005). Townsend (2001) showed that hydroperiod is the dominant control of woody vegetation composition on the lower Roanoke River floodplain, and that extremely wet years (90th percentile) are the most important hydrologic characteristic controlling composition. An extremely important hydrologic alteration on the Roanoke in terms of forest regeneration has been the extended duration of periods of high water during the growing season (Richter et al. 1996, Pearsall et al. 2005). Fig. 1-2 shows hydrographs for pre-dam and post-dam mean flows, and Fig. 1-3 shows the length and frequency of flood events

(defined as periods of flow over 326 m^3 for 5 days or more) for both current dam operations and those of pre-dam flows as based on a model from Pearsall et al. (2005). To date, attempts to design and execute a more natural flow regime have fallen short, as the U.S. Army Corps of Engineers remains intent on protecting a small group of downstream farmers from flooding (J. Richter, personal communication, July 2010).

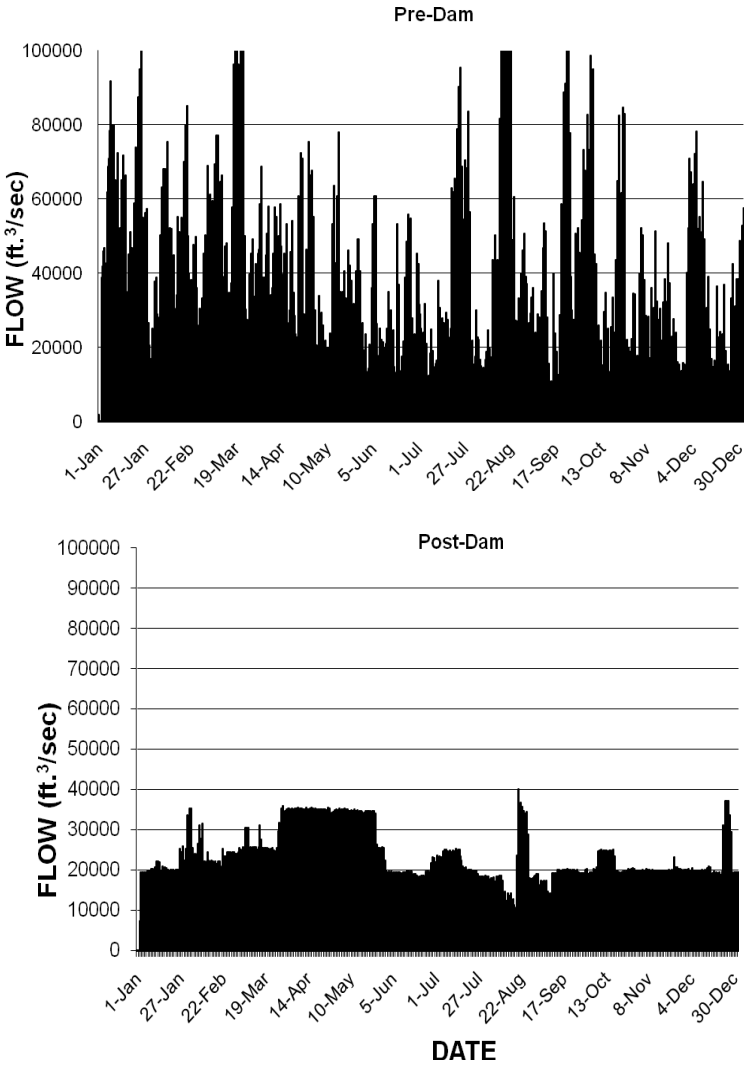

Figure 1-2: Mean pre-dam (1912-1950) and post-dam (1951–1995) flows immediately below Roanoke Rapids Dam (approx. 120 river km upstream of study site). Note difference in scale between pre- and post-dam graphs.

Sustained periods of high water with few periods of low flow and pulses of very low flow have led to an apparent decrease in regeneration survival of bottomland hardwood canopy species such as overcup oak (*Quercus lyrata* Walter) and green ash (*Fraxinus pennsylvanica* Marsh.) (Pearsall et al. 2005). The Broadneck Swamp backswamp typically remains flooded longer than bottomland hardwood zones, and these extended growing-season floods have very likely also prevented successful baldcypress and water tupelo regeneration in years which would have been conducive to such regeneration in an unregulated regime. Extended growing season flooding also impacts

seed production, dispersal, and long-term seedling growth on the floodplain (Hochman 2004).

Low flows later in the growing season and relatively low flows and/or only brief periods of high flooding during 1 or more subsequent growing seasons are essential for successful canopy-tree regeneration. Souther and Shaffer (2000) found that, in clear water, young seedlings growing in full sun could survive being overtopped for roughly a month to 45 days. However, in 20% sun – levels well above those in the understory of the Broadneck Swamp – seedlings could only survive overtopping for roughly 14 days. In dark, tannin-stained water, these times are likely even shorter.

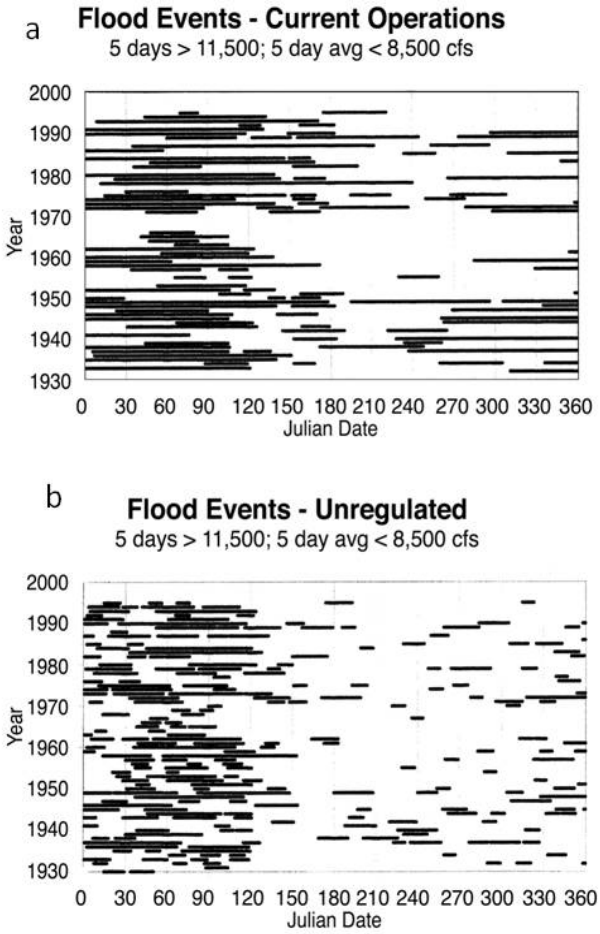

Figure 1-3: Floods at a Broadneck Swamp gauge, a) status quo *vs. b) unregulated operations. Based on 1 year of data, flood initiation was set at 5 consecutive days of more than 326 m^3/sec, and flood reset was set at 5 consecutive days of less than 241 m^3/sec. Used with permission from Pearsall et al. (2005).*

Backswamp areas of the Broadneck Swamp flood to depths of 1.5 – 2 m (personal observation) during periods of extended high flows (>284 m^3/sec). Three man-made logging inlet canals have long served to alter local hydrologic patterns at the study site (see Fig. 1-1). Aerial photos show these canals were constructed sometime after 1938, probably in the 1940's or 50's (J. Richter, personal communication, Aug. 2008). During periods of high flow, the canals funneled water directly onto the floodplain, which caused faster and presumably deeper flooding in the local area than would occur if the only

source of water were natural distributaries such as Duck Gut and Black Gut (Fig.1-1; J. Richter, personal communication, Aug. 2008). The Roanoke's main channel only rarely floods its banks directly. Inlet canals also funnel water out of the swamp once levels in the channel drop below roughly 311 m^3 (J. Richter, personal communication). Since these canals lead to unnatural patterns of flooding, they were fitted with immovable steel walls in the fall of 2008 to prevent flow. A leak in one of the walls was not repaired until summer 2010. The influence of the walls on hydrology at the study site will not be known until sufficient data from water level recorders can be acquired to compare with pre-wall data. Until then, it would likely be unwise to use pre-2008 hydrologic data in models predicting current or future hydrologic conditions at the site. Black Gut (Fig. 1-1) has been and remains the primary conduit of water input to and output from the floodplain.

Dams have also had strong effects on the sediment load within the channel itself as well as patterns of sedimentation in the floodplain along different reaches of the river (Hupp et al. 2009a). Dams typically trap upstream sediment (Brandt 2000), and, since the Roanoke has no substantial tributaries below the dams, sediment inputs must come from erosion and entrainment of bed and bank sediments (Hupp et al. 2009a). Bank erosion rates, especially mass wasting, are especially high on the middle reaches of the Roanoke River and may be the cause of the net deposition (a 2.8 million m^3/yr surplus) occurring along the floodplain of the lower reaches of the river (Hupp et al. 2009b). Flow regulation has caused a loss of flood peaks which typically build levees, and this has forced most of the sediment deposition to occur in low backswamp areas of the floodplain (Hupp et al. 2009b). Though this sediment deposition could lead to a flatter, less topographically diverse floodplain (Hupp et al. 2009b) and potentially more areas likely to support regeneration establishment, the full effects of strong sedimentation on baldcypress and water tupelo growth are unknown. Early reports show that even very

small amounts of sedimentation (0.1 - 0.4 cm/yr) in small-stream riparian forests were associated with declines in overall litterfall, woody biomass production, fine root production, leaf area index, and shrub biomass (Jolley et al. 2009). The long-term consequences of dam-induced sedimentation at the study site on adult or sapling growth are unknown.

The interaction of dam-induced alterations in hydrology and sedimentation with low adult baldcypress abundance and low-light sub-canopy seedling/sapling growth, is likely a primary factor in the lack of consistent and widespread regeneration of the species in Broadneck Swamp. Water tupelo regeneration is even rarer than baldcypress at the study site, likely for the same reasons. An understanding of the low-light growth patterns and ages of current Broadneck Swamp saplings would undoubtedly help clarify conditions necessary for seedling establishment and what can be expected in terms of long-term diameter growth.

Broadneck Swamp and Specific Study Site Characteristics

The active Roanoke River floodplain is roughly 2 – 2.5 km wide at Broadneck Swamp. As noted above, flooding at the study site is only very rarely due to overbank flooding from the main channel. Rather, natural distributaries (*e.g.*, Black Gut – Fig.1-1, and Coniotte Creek) and man-made inlet canals are vectors of water to the backswamp and higher bottomland elevations if rainfall is high enough.

The canopy in backswamp zones of Broadneck Swamp is dominated by water tupelo. Adult baldcypress are usually somewhat taller than the floodplain's mature water tupelo, but these large baldcypress are relatively rare. They occur singly or in small groups across the floodplain. Living old-growth baldcypress (well over 120 cm dbh) are even rarer but seemingly uniformly scattered across the backswamp.

The reasons for the current water tupelo dominance in the backswamp are unknown, but it is likely that harvesting efforts targeting baldcypress over many years led to conditions favoring water tupelo. On a large scale, selective harvesting could have reduced baldcypress seed production across the floodplain to a point far below that of water tupelo. Baldcypress seeds generally do not remain viable for more than a year (Middleton 2000), and a low percentage are viable at any one point (Schneider and Sharitz 1986), so a long-term local seed bank would not have existed following massive harvests. Water tupelo has been shown to seed in and grow rapidly in 0.81-ha clearcut patches, showing 672 seedlings/ha at 93.9 cm three years following harvest (Gardiner et al. 2000). Also, even where baldcypress seeds would have been able to germinate in open conditions across the floodplain, water tupelo generally outgrows it at very young ages in high-light conditions (Pezeshki 1990, Keeland and Conner 1999, but see Conner et al. 1997), and may have established dominance so that it shaded out most baldcypress and prevented rapid growth and immediate entry into the canopy. Conversely, baldcypress has been shown to outgrow the shade-sensitive water tupelo in conditions of lower light (Dulohery 2000).

As mentioned above, neither tupelo (Huenneke and Sharitz 1990) nor baldcypress (Demaree 1932) can germinate in standing water, but require periods of unflooded soil to become established. Flooding following periods of harvest could have been such that both species germinated during dry periods of spring and summer, and only (mostly) water tupelo seedlings were able to grow to heights tall enough to prevent being overtopped by floods of the following winter and spring. There are no herbivores known to target baldcypress systematically over water tupelo. Nutria (*Myocastor coypus*) have been known to systematically kill baldcypress regeneration (Conner et al. 1986), but this species has never been known to occur at the study site. Beaver (*Castor canadensis*) occur widely at the study site, and likely had larger populations during times of current

canopy tree establishment (Townsend and Butler 1996). Though beavers do clip and kill baldcypress saplings at the study site, they do so in relatively small proportion to the number of saplings currently occupying the area. Beaver will choose other species to forage over baldcypress if available (Townsend et al. 1996), and clipping of saplings may occur during flooding when access to other species is restricted. It seems unlikely that beaver or another potential threat to baldcypress seedlings – feral pigs - ever existed at levels necessary to be the sole reason for current water tupelo dominance. However, coupled with systematic reduction in seed-bearing adult baldcypress via harvesting, these herbivores certainly could have played a role.

The understory and midstory across the study site are relatively open, and very few shrubs and young saplings exist. At the scale of the entire forest, very little regeneration of either major canopy species exists. Though abundant water tupelo germination occurs during years with little to no flooding in spring and summer (personal observation), very few water tupelo saplings roughly the size of baldcypress saplings exist on the floodplain. McKnight (1981) and Kolka (1998) suggest water tupelo is less tolerant of shade than baldcypress, and it often outgrows baldcypress as a seedling in high light conditions (Pezeshki 1990, Keeland and Conner 1999). It is possible that low light prevents water tupelo, classed as shade intolerant by Johnson (1990), from attaining the height necessary to survive future flooding, and this is why it is poorly represented in the midstory.

In contrast, some areas of the floodplain are densely populated with sub-canopy baldcypress saplings ranging in diameter at breast height (dbh) from >1 cm to <25 cm. These saplings tend to occur in relatively dense clusters, or bands, roughly parallel to "transition zones" from low-lying, deeply flooded backswamp to higher, generally drier areas closer to the river. Sapling clusters also occur on some (but not all) isolated ridges within the backswamp. In general, baldcypress saplings in these pockets appear stunted,

showing little to no growth, excessive epicormic branching and, in some cases, crown dieback. In some of the denser areas, a large percentage of the saplings appear close to death or are already dead. The signs of stress exhibited by saplings in these areas are no doubt a combination of prolonged growing-season flooding and a lack of light due to the dense canopy generally overtopping them. Superficially, it appears that light may be the stronger of the two limiting growth factors as saplings growing in natural gaps in the canopy are usually taller and growing more vigorously than nearby saplings beneath a full canopy. Also, most of the clusters are high in density, and the saplings' mutual competition is an obvious added stress.

Objectives

It is clear that a better understanding of baldcypress growth is necessary if the species is to be utilized within the framework of two-aged or uneven-aged silvicultural systems using patch cutting. Advanced regeneration can shorten rotations and reduce the need for site preparation and or planting if it exists widely enough (Ferguson and Adams 1980). Little is known regarding baldcypress' light requirements beyond the seedling stage, or how these requirements may change over time. Though sapling growth response to "release" via killing overstory trees has been studied for many other tree species (*e.g.*, Wright et al. 2000), such characteristics of baldcypress are unknown.

In an effort to restore baldcypress to a greater proportion of the floodplain's canopy – as it is thought to have once been dominant (Wharton et al. 1982) – the U.S. Fish and Wildlife Service, who owns and manages the Roanoke River National Wildlife Refuge, is attempting to use artificial canopy gaps to enhance growth of sub-canopy baldcypress to increase their presence within those gaps. This study was established as a pilot project to test the ability of long-stunted baldcypress saplings to respond with diameter growth to increased light and soil resources. An additional objective of the study

was to determine woody species composition across the Broadneck Swamp and thereby gain insight into a) the true relative dominance of water tupelo across the backswamp and other areas and b) the abundance of sub-canopy baldcypress regeneration potentially available for utilization in future restoration efforts.

Specific objectives of this study were to:

1) Determine the initial growth response of baldcypress advanced regeneration to significantly increased light conditions from artificially created gaps

2) Determine the early effects of increased light resources on mortality and structure within dense sub-canopy baldcypress clusters;

3) Determine the spatial variation in woody species composition of the defined area of the Broadneck Swamp floodplain, especially canopy and sub-canopy baldcypress and water tupelo; and

4) Accurately age sub-canopy baldcypress saplings with the intent of improving understanding of the species' shade tolerance and ability to respond to release

CHAPTER 2 – METHODS

Artificial Canopy-Gap Experiment

Plant Area Index and Diffuse Non-Interceptance

Leaf Area Index, or, more accurately, plant area index (PAI), is a measurement of the one-sided foliage area (green leaves as well as anything else blocking sunlight – branches, twigs, flowers, etc.) per unit ground area – a dimensionless value. PAI was indirectly measured on all plots with two LICOR 'LAI 2000' Plant Canopy Analyzers (PCA's). These PCA's allow inference of canopy density by measuring light levels both outside the forest canopy and at multiple points beneath it. Leaf area index is, of course, directly related to sub-canopy light but is also correlated with productivity (Vose and Allen 1988).

The fraction of sky not blocked by foliage is known as diffuse non-interceptance (DIFN). DIFN ranges between 0 (no sky visible) and 1 (no foliage visible), and is the closest metric to being an indicator of "canopy light absorption" produced by LICOR's PCA (LICOR 1992). DIFN has been utilized in many other studies, often as measured via hemispherical fish-eye photography (Davies-Colley and Rutherford 2005). It can be understood as the fraction of sunlight within the photosynthetic spectrum available at the point of measurement (Davies-Colley and Rutherford 2005). In examining light conditions within varying levels of disturbance in northern hardwoods in plot sizes very similar to those used in this study, Rhoads et al. (2004) found "for a quantitative measure of canopy disturbance at a large plot or forest stand scale, the LAI-2000 appears to provide an accurate and precise measure."

If one is measuring PAI and DIFN of a tall canopy that cannot be simply "overtopped," two PCA's must be used – one beneath the canopy and one in a large gap

or clearing outside the measured canopy but as close to it as possible (LICOR, 1992, Rhoads et al. 2004). Below-canopy measurements are known as "B-readings" and measurements in the clearing, or above-canopy, are known as "A-readings." Due to the necessity of measuring available light both before and after treatment, exact points of initial B-readings in each 19 x 24m plot were marked for re-measurement (Fig. 2-1).

Prior to taking B-readings, several decisions must be made concerning how to allow the PCA's sensitive light sensor to "view" the canopy. If readings are to be taken by an individual holding the below-canopy sensor and moving it around to different points within the plot, which was the case in this study, a view cap is necessary which blocks the operator from its field of view. This can be done with a "270 degree" view cap, or one in which 90 degrees of the circular sensor can "see" the canopy, and the 270 degrees of the sensor closest to the operator are covered. Such a cap also aids in blocking from the field of view canopy gaps somewhat distant from the canopy overhead the point of measurement. Such gaps are best wholly measured in one or a few sensor readings directly below them since an underestimation of PAI can occur if a sensor "sees" little or no foliage in one direction and dense foliage in another direction. This causes the gap to be over-weighted (LICOR 1992).

This issue is also why the design of measurement layout within each plot was chosen. Fig. 2-1 illustrates the measurement layout design for below-canopy readings. Four readings were taken 4 m from each rectangular plot's long side. One reading was taken 2 m from each corner; one reading was taken 4 m from each short side; and one reading was taken in the center of the plot. Measurement points were spaced at differing distances from the plot boundary to provide a spatially comprehensive sampling of the plot canopy (Fig. 2-1).

Since future treatment would lead to plots becoming a large gap in the canopy, all B-readings were oriented toward the center of the plot – aka the future gap – so as to avoid the problem described above (in addition to using the view caps). Error is reduced by orienting the two sensors in the same direction for each matching measurement (LICOR 2000). The nearest easily accessible clearing of appropriate size to study plots was 3.2 km away. Cell phone and radio communication were not possible over that distance in the remote, heavily forested area, and thus a single A-reading azimuth was chosen and consistently used – 58 degrees NE. Direct sunlight causes reflection which illuminates the undersides of leaves and leads to underestimation of PAI and overestimation of DIFN by the PCA (LICOR 2000). A- and B-readings should not be taken when the disc of the sun is directly visible in the sky. Thus, all readings were taken 1-10 minutes pre-dawn or post-dusk or when the sun was blocked by dense cloud cover. In each plot, 15 B-readings were taken (Fig. 2-1). No previous studies documenting PAI or DIFN within baldcypress-tupelo forests have been published, and levels of variability in PAI within this forest type are unknown. In an unpublished study, 10 B-readings in 10 m x 10 m plots in baldcypress stands proved to be more than enough to capture the range in variation in canopy density of the plot within an acceptable level of error (R. Keim, Personal Communication, July 2008). Plots in this study were substantially larger (19m x 24m), and 15 readings per plot were taken. Parker et al. (2008) used 10 measurements to measure light conditions of 225 m^2/plots in red pine (*Pinus resinosa* Aiton) plantations.

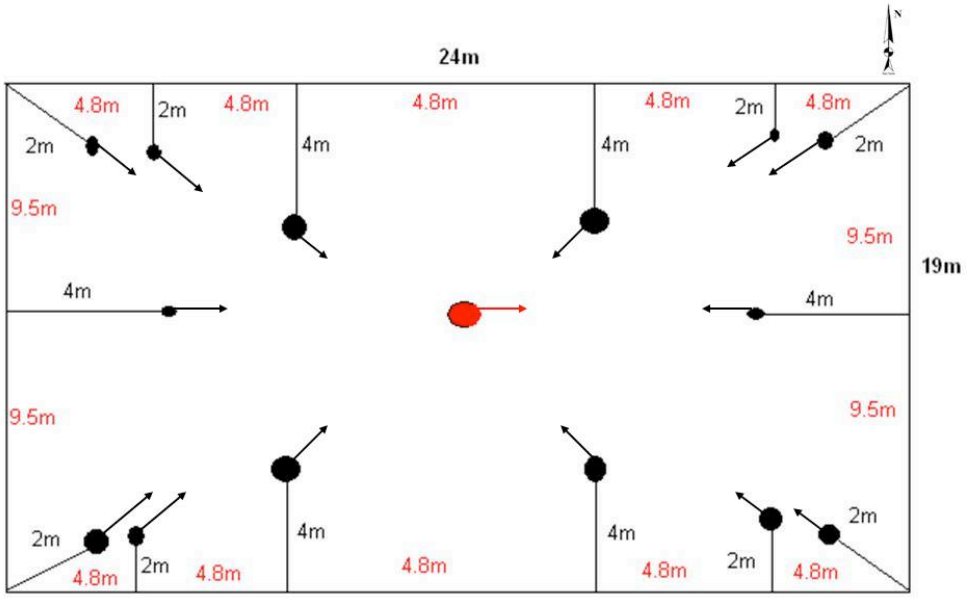

Figure 2-1: The layout of sampling points for below-canopy PAI readings taken in every plot. The small black numbers represent distance of the measurement point from the plot boundary, and the red numbers represent the distance along plot boundaries between each measurement point. Arrows note the direction readings were taken – facing the center of the plot, or, in the case of the center- point reading, facing east.

Initial plans called for the re-measurement of PAI directly following the 2009 growing season. However, given the survival of a few canopy trees in most of the treatment plots, it was decided that re-measurement of canopy conditions would best be done following the 2010 growing season. Even if all trees had died and lost their leaves, flooded conditions extending into late summer 2009 would have likely prevented PAI measurement in the remote study area because of the difficulty in accessing sites at dawn and dusk.

Vegetative Sampling

Due to the fact that baldcypress saplings are generally present in clusters within the Broadneck Swamp study area and not evenly or randomly spread, sample plots (Fig. 2-1; 24 x 19m) established for the artificial gap experiment were placed in a biased manner around groups of saplings with specific characteristics. Initially, 14 pairs of plots were established. At the outset, plots were established to capture a range of variation in

sapling size and density occurring across the study site, but paired plots were located as closely as possible so as to minimize variability in canopy tree characteristics and hydroperiod across different areas of the floodplain. All plots were established in backswamp areas dominated by water tupelo and much rarer adult baldcypress. This region included transition zones where most areas of high density baldcypress regeneration occur between the low-lying backswamp to higher, more species-rich bottomland hardwood regions. These transition zones, which exist near the interface of the active floodplain's only two soil types (Fig. 2-3), are often occupied by a far greater abundance of Carolina ash (*Fraxinus caroliniana* Mill.) in the midstory and occasionally species besides water tupelo and baldcypress in the overstory, such as overcup oak, green ash, swamp cottonwood (*Populus heterophylla* L.), red maple (*Acer rubrum* L.), and American sycamore (*Platanus occidentalis* L.).

Given the long-term goal of restoring baldcypress to the canopy stratum within artificial canopy gaps, height growth would be the ideal metric for studying growth response to gaps. However, for this short-term (2-year) study, diameter was chosen as the growth metric because height growth is generally strongly dependent on conditions in the previous year (Ferguson and Adams 1980). Also, height growth fundamentally requires diameter growth for mechanical support (Guan et al. 2008). Previous studies have suggested that diameter growth is last in the carbon allocation priority ranking for trees (Waring 1983, Waring and Pitman 1985), and thus any diameter growth suggests that a tree has acquired enough resources to meet demands. Diameter growth should thus be an effective indication of a tree's overall health and productive efficiency (Larocque 1998). On the other hand, Nilsson and Albrekston (1993) argue that under intense competition for light, diameter growth becomes a high priority. Either way, diameter growth should be a robust measure of a tree's competitive ability (Guan et al. 2008).

Plots were arranged to include sapling clusters of varying size and density by observation. Though it was apparent there was some variation in size within clusters, this variation appeared minimal in relation to average cluster size across regions, thus facilitating the notion that clusters included individuals of roughly the same age or cohort. Plots were 19x24 m in size and spatially arranged to capture the desired sapling cluster appropriately. Plots were not established beneath existing natural gaps and were kept at least 20 m from areas in which sizeable canopy gaps already existed. Paired plots were initially placed as close as possible to each other while still adequately capturing sapling clusters visually similar in average size and density and while avoiding canopy gaps. Treatment plots and control plots were kept at least 30 m apart (all but one pair were considerably farther apart than this), though several control plots were near other control plots.

PVC stakes were placed at each corner and ropes were run from corners to corner to create easily recognized boundaries. In each plot, stems breast height and taller than 1.37 m were measured for diameter with a standard diameter tape (d-tape). On stems with no buttswell at breast height, diameter was measured at breast height. On stems with appreciable buttswell at breast height, diameter was measured at 2 m. This was sufficient to measure above buttswell for most canopy trees of water tupelo and adult baldcypress. Some large stems exhibited buttswell higher than 2 m, and these were measured at 10 cm above the point where buttswell was visually determined to end.

Baldcypress "saplings" were uniformly defined as baldcypress stems breast height and taller but below 25 cm diameter at breast height (dbh). This upper limit was chosen based on visual observations that stems 25 cm and larger were entering or had already entered the lower levels of the canopy stratum, and thus might not be subject to the same low levels of light as smaller individuals. The vast majority of saplings within the study

area were smaller than this upper limit. In every plot, all baldcypress saplings were individually tagged and measured for diameter just below the point of tagging.

Tags were attached with either a durable outdoor zip-tie or a nail. Zip-ties were used in abundance at first because of speedier installment, but it was quickly discovered that gray squirrels (*Sciurus carolinensis*) were fond of chewing the plastic and causing them to fall, especially in the driest areas. Though the point of measure was recorded in cm height along the stem, this loss of a zip-tie meant that the original point of measurement had to be estimated within a specific area of the stem, which is problematic when small amounts of growth or non-growth are to be potentially detected. Thus, nails were used on all saplings 4 cm and greater in diameter. Saplings smaller than this were deemed likely to be injured by a nail.

On saplings where zip-ties were left, they were attached just above a relatively sturdy branch unlikely to break during the course of the study. Diameter was measured 1 cm below the branch, or at the point where the branch collar no longer influenced the size of the main stem. On some small individuals, there were no suitable branches located within the 1.25 – 1.65 m target zone for zip tie and nail placement. There was no option but to attach the zip tie at excessively low or high positions on these saplings. Thus, initial diameter statistics for saplings include some variation in size due simply to location of measurement on the stem, and should be viewed with caution. Though large trees allocate resources to particular parts of the stem during periods of growth, the relatively small amounts of diameter growth detected in this short study were not likely influenced by the location of measurement. Nailed saplings were measured 1 cm below the nail.

All saplings < 8 cm at the nail or zip-tie were measured with digital calipers, which are able to detect diameter to the nearest hundredth of a mm (two measurements

were taken and averaged). However, this was rounded to the nearest 10th of a mm and later converted to cm. Growth statistics were calculated in cm. Larger saplings were too wide for the calipers and were measured with a standard d-tape, which is accurate to the nearest 10th of a cm (mm). Stems were considered "in" if they were rooted inside the plot.

Every baldcypress sapling was provided with a "Viability Number," which is simply a visual subjective assessment of its initial overall health. Viability numbers ranged from 0 – 3, and represented the following visual grades of health:

0: The sapling appeared very healthy with a full crown and little, if any, epicormic branching visible.

1: The sapling appeared to be growing at a slow rate and had sprouted epicormic stems or leaves along crown branches and/or along the bole, but the crown was generally whole and the sapling firm.

2: The sapling was very weak, dying, or close to death, with excessive epicormic branching in many areas, often with crown dieback, and often with a noticeably weak main bole.

3: The sapling had noticeable beaver damage, usually in the form of a clearly clippedmain stem, above which one or multiple smaller sprouts had emerged.

Though beaver damage is extensive on saplings in some areas of the floodplain, most of it appears older (at least one or two growing seasons worth of sprout growth), and most plots had only 0-3 measurable clipped saplings. If growth varies significantly across visual viability classes, they could be useful in determining justification of release of specific groups or individual understory saplings in the future.

It is important to note that the sampling methodology for baldcypress saplings in this study was not ideal. Tags, and therefore the diameter measurements based on tag placement, were not uniform in terms of height along the bole. This means that comparisons of growth response between trees based on initial diameter may have to be viewed with a some caution because initial diameters may not necessarily equate. For

example, two saplings with the same recorded diameter may actually be of slightly different sizes because on one diameter was recorded near 1.65 m and on the other the measurement was taken at 1.25 m. In general, this sampling regime had to be carried out because many saplings were too small to reliably use a nail at a standard-height measurement point. It was decided that the amount of variation within this height zone was small enough to be able to utilize the results of the study as intended.

Plots contained saplings of highly variable densities. In 6 plots with over 120 saplings, a sub-sampling regime was established in which four 4 m x 4 m sub-plots were sampled in the same fashion as noted above. One sub-plot was established in each corner 4 m from the plot's long side and 5 m from the plot's short side, and all saplings within these sub-plots were measured as above. Plots were initially set up in August – November, 2008, and initial measurements of all saplings and canopy trees were carried out in September – November, 2008.

Dendrometer Bands

In every plot containing baldcypress saplings of sufficient size, at least one sapling > 8 cm dbh was equipped with an expandable stainless steel dendrometer band to measure minute (tenth of a mm) changes in diameter over time. Dendrometer bands have been employed in a variety of long-term tree growth studies, including many involving baldcypress and water tupelo (see Day 1985, Conner and Day 1992, Keeland and Sharitz 1995). This was done in an effort to determine the accuracy of using a diameter tape to record changes in diameter of larger stems over only one or two growing seasons. Bands were checked twice during 2009 and once during 2010 for circumference growth, which was later converted to basal area and diameter increments. They were checked for growth at the same time as un-banded saplings in each year. Dendrometer bands have been shown to underestimate baldcypress growth in their first year of measurement (Keeland

and Sharitz 1993) as it takes time for the band to settle tightly to the tree. To avoid this, growth should not be recorded until at least one growing season following band installation (Keeland and Sharitz 1993). In this study, bands were installed in August 2008 and first checked for growth in August 2009.

Plot Pairing

Following a review of the initial plot structural characteristics, it was determined that most plots initially paired based on proximity to each other and visual assessment of sapling density and average size were quite different in terms of canopy tree characteristics (basal area, density, size) and sapling characteristics (basal area, density, and size). Because plots very near each other showed a high degree of difference in terms of overstory tree characteristics, pairing based primarily on proximity was disregarded. Rather, it was decided that pairing based on the measurable plot characteristic most likely to influence growth response would be the wisest option. Based on many previous studies showing initial size to be very important to advanced regeneration response to release (Murphy et al. 1999, Krasowski and Wang 2003), initial sapling diameter was chosen as the widely measurable plot characteristic likely to have the most influence on growth response to canopy gaps. It is likely that height is the most important factor in terms of the response of an individual to release relative to its neighbors, but diameter and height are strongly positively correlated in baldcypress (and most trees) (Parresol 1992).

Thus, prior to treatment, plots were re-paired with the plot of closest quadratic mean diameter (Dq), or the diameter of the tree of average basal area. This was done in all cases except where two plots to become treatment plots would have been too close in proximity, or where potentially paired plots were excessively different in initial total sapling basal area. The latter issue was an issue in only one potential pairing. One isolated plot pair was thrown out for being too far from the primary areas of baldcypress

regeneration, and two other plots were thrown out for having extremely high (384) and excessively low (19) numbers of saplings. Prior to alternative plot pairing, the difference between Dq among paired plots averaged 1.19 cm compared to 0.43 cm following the new arrangement. This new difference is about 8% of the overall mean. However, other metrics of potential difference between the plots remained relatively high, including an average difference of 0.111 m^2 in sapling basal area (approx. 50% of the overall mean), 0.759 m^2 in canopy tree basal area (approximately 25% of the mean, and 122.4 stems/ha (approximately 28% of the mean). These pre-treatment differences among the paired plots – especially differences in sapling basal area – could have had some effect on growth response and are a potential source of error in the data.

Saplings in Natural Gaps

Though natural gaps of multiple adjacent dead trees are somewhat rare across Broadneck Swamp, and gaps with baldcypress saplings beneath them are even rarer, such gaps could potentially provide clues to the long-term response of sub-canopy trees to release. It is impossible to know how long a gap has existed and therefore how long a sapling has been released within it. However, if saplings released in the experiment were to respond with strong growth and saplings in these natural gaps showed stagnant, very low, or no growth, they may be viewed as potential evidence of a plateau effect or the inability to maintain growth at all. In August 2008, 10 saplings larger than 8 cm diameter growing within natural gaps of various sizes (all created by at least two adjacent adult canopy dominant/codominant tree deaths) were fitted with dendrometer bands. Circumference growth was checked in August 2009 and August 2010, and these values were converted to diameter increment (cm) and basal area increment (cm^2).

Repeated Measurements

Baldcypress sapling diameters were re-measured in mid-August, 2009 and 2010. Saplings were re-measured as close as possible to the original measurement point. Saplings were measured with both digital calipers and a d-tape if they had not grown too large. Keeland and Sharitz (1995) noted that in slightly higher areas of the Savannah River floodplain (comparable to the Roanoke River floodplain) – those dominated by bottomland hardwoods, swamp tupelo, and scattered baldcypress - understory baldcypress saplings grew well into mid- to late-August. However, in deeper backswamp zones, growth was cut short earlier, usually in early to mid-August. Thus, it was reasonable to expect Broadneck Swamp backswamp saplings in this study, which are flooded heavily in spring and at times during summer and fall, to cease growing by mid-August.

Treatment

In early December 2008, all non-baldcypress stems (sub-canopy and canopy trees) in each of 12 treatment plots were girdled completely at breast height with hatchets and/or machetes, and open wounds were sprayed with the herbicide *Habitat* (Fig. 2-2). Any non-baldcypress with foliage overtopping any portion of the plot, however slight, was treated. Thus, actual canopy gaps were somewhat larger than the 456 m^2 contained by the plots. *Habitat* is an Imazapyr-based herbicide labeled for use in aquatic and wetland ecosystems (BASF 2004), which is the primary reason it was chosen for this study. Imazapyr is the primary active ingredient in many non-selective broad-spectrum herbicides such as *Arsenal*, *Chopper*, and *Assault* (Tu et al. 2004). It is absorbed by both foliage and roots and causes the disruption of protein synthesis and wilting of leaves,

eventually starving the plant. It is a very low-risk chemical in terms of damage to animals and insects (BASF 2004).

Imazapyr is persistent in soil for up to 5 months and can contaminate local groundwater, possibly leading to the defoliation or death of non-target plants (Tu et al. 2004 and see Eck and McGill 2007). However, Dixon and Clay (2002) found no effect of Imazapyr-based herbicide application of *Rhododenrons* on nearby individuals of the same genus via root transfer. This was a concern early on in this study (a 50% mixture was being used because of the size of the trees being treated), with the possibility that the herbicide might "leak" from water tupelo roots into the surrounding soil and cause stress or death to nearby baldcypress saplings.

By June 2009 the great majority of foliage in treatment plots was gone and most of the large canopy trees were dead or dying. However, a handful of large trees (1-10) in each plot held onto a significant amount of leaves. Since no studies on treatment of tupelo or very large canopy trees with *Habitat* could be found, it was unknown whether these individuals would soon die as well or had greater root reserves and would hold onto foliage into the next growing season. Since creation of as complete a gap as possible was of the utmost importance to study objectives, a re-treatment of all trees which had held some or all of their leaves during the 2009 growing season was carried out.

Fig. 2-2: Water tupelo in a treatment plot following girdling and spraying, Dec. 2009

This treatment was conducted during December 2009 by making a series of notches (12.5 - 25 apart) around the tree above the original girdle line and painting the notches with herbicide. It was found upon wounding the survivors that most contained living cambium in only small sections of the trunk and the majority of wood was already dead and rotting.

Imazapyr-based herbicides may be applied at many different times of year, depending on target species and weather factors. *Habitat* used in cut-surface treatments to woody species is best applied at any time heavy sapflow is not occurring (*i.e.* spring and summer; BASF 2004). A December 2008 application for this study was chosen because of availability of assistance from technicians and dry conditions at the study site.

Statistical Analyses

Plant Area Index and Diffuse Non-Interceptance

PAI and DIFN were averaged by treatment for 2008 and 2010, and differences within plots between treatment and control were examined using paired t-tests (PROC Ttest, SAS 2010).

Artificial Canopy Gap Experiment

Initial diameters of all untagged trees were averaged by species and plot and also across all plots to provide simple means of density (number of stems/ha or m^2), basal area (m^2/ha), and size [Dq]). These values were used in comparing potentially paired plots and as a comparison with similar values from the forest-wide survey of the floodplain.

To provide an integrative idea of each species' contribution to overall community makeup species Importance Values were utilized. Importance Values combine density, basal area, and frequency (how often the species occurs across plots) to provide a more complete picture of competitive interaction and structural makeup of an area because each one of the indices used alone could provide a different notion of which species are dominating and which are less important. For example, in Broadneck Swamp, use of density alone might enhance the importance of Carolina ash, which occurs in the understory in many areas in great numbers. However, when basal area and frequency are taken into account, the relatively small, spottily distributed Carolina ash would become less important. Because the importance of individual species is being sought within the context of an ecological community, relative density, relative basal area, and relative frequency are used. For the Artificial Canopy Gap Plot analysis, importance values were calculated according to Mueller-Dombois and Ellenburg (1974), originally conceptualized by Curtis (1959).

This required that for each species found in canopy gap experiment plots, the following calculations were used:

1) Relative Density = $\frac{\text{number of stems of species (across all plots)}}{\text{Total number of all stems (across all plots)}} \times 100$

2) Relative Dominance = $\frac{\text{total basal area of a species (across all plots)}}{\text{Total basal area of all species (across all plots)}} \times 100$

3) Relative Frequency = $\frac{\text{Number of plots in which a species occurs}}{\text{Total number of plots}} \times 100$

In this way, three percentages are used for each species. Each of these percentages is summed for each species, divided by 3, and multiplied by 100. This provides a numerical importance rank which, when added up across all species, equals 100.

Of course, because artificial canopy gaps were set up in a biased manner to include dense clusters of baldcypress saplings, baldcypress is strongly over-weighted relative to its importance across much of the floodplain. These importance values simply provide an indication of the most dominant species within the canopy gap experiment plots themselves. However, as an alternative, the canopy gap experiment importance value for baldcypress was recalculated without saplings included to provide a comparison of the importance of overstory baldcypress in areas where saplings are abundant to areas where they are less abundant or absent.

All growth data was rounded to the cm level for all analyses and reporting. Growth from other studies, for comparisons with results of this study, were similarly converted to the cm level if not already in cm. Diameter increment growth was converted to Basal Area Increment (BAI, in cm^2) for use in statistical analyses of growth, but diameter increment values are also reported for many analyses because BAI has been infrequently used in past studies. Though this study deals with a relatively short time scale and relatively small amounts of growth, BAI is preferred over normal diameter increment because it reduces the effect of decreasing ring widths and annual variation which occur naturally as trees age and diameter increases (Ewel and Parendes 1984, Hesse et al. 1998). Though there is no difference between using diameter increment and BAI in the precision of estimates of future diameter (West 1980), basal area growth is more linearly related to tree volume growth (Hokka and Groot 1999).

Many past studies of plant growth have used mean relative growth rate (MRGR) as a primary metric to reduce the effect of initial size on growth response to some environmental or genetic cue (South 1995). MRGR also quantifies growth *efficiency*, and

the term was originally known as the "efficiency index of dry weight production" (South 1995). However, mean relative growth rates are problematic because they ignore the fact that the amount of plant growth in a unit of time is a percentage of the size of the plant but that this percentage often changes as tree size changes (South 1995). This percentage often decreases as trees get larger. Calculating the Mean Relative Production Rate (MRPR) reduces error associated with this problem by calculating growth of intervals of time over time, thus removing the influence of previously accumulated biomass (Brand et al. 1987, South 1995). However, this method requires at least four measurements of plant size through time. This study currently has only three measures, and cannot utilize MRPR.

BAI is itself a relative growth measure which accounts for differences in initial tree size (Allen et al. 2005, Krauss et al. 2009). Both BAI and diameter increment displayed non-normal distributions for all years (2009, 2010, and both years) and treatment combinations. This was primarily due to the large number of saplings showing 0 or very little growth, especially in control plots but to a lesser abundance in treatment plots as well. This skewed the distributions considerably, but typical data transformation techniques were ineffective in producing normal distributions because of the large number of 0's in each data set. Thus, non-parametric methods (using sample medians) were employed in analyzing all growth data.

BAI and diameter increment differences between treatments within years were examined with Wilcoxon Rank Sum tests (aka Mann-Whitney U test; Proc Npar1way; SAS 2010), the non-parametric equivalent of t-tests for two independent samples. A Wilcoxon Signed Rank test ("Sign Test"; Proc Univariate; SAS 2010), a non-parametric equivalent of the paired t-test, was used to sample growth differences within treatments across years. Growth analyses were performed on all saplings grouped by treatment

and/or year. BAIs and diameter increments were also averaged by plot and then averaged by treatment in addition to grouping all saplings by treatment alone.

Paired plots were compared with paired t-tests following square-root transformation of plot averages in both treatments so that the difference between paired averages would be normal. This was done for 2009, 2010, and both years. Also, the difference between each plot pair's two year mean BAI and diameter increment were regressed on initial plot mean Dq, and tested for significance.

BAI was similarly used in examining relationships between initial sapling diameter and growth. These relationships were examined in several ways. First, sapling basal area and diameter increment across all diameters were examined with a Spearman Rank Correlation (Proc Corr; SAS 2010). Spearman's rho (r_s) provides an indication of how well the correlation of ranks of two variables may be described by a monotonic function. A +1 or -1 would indicate a perfect monotonic correlation between the two variables. Thus, r_s is comparable to the Pearson Product Moment Correlation metric r of classic parametric correlation (SAS 2010).

Secondly, saplings were grouped by initial diameter into 2 broad classes – those less than or equal to 5 cm dbh and those greater than 5 cm dbh. This initial diameter was used because it appeared to represent a general cutoff point between the mean sizes of saplings within differing areas of the floodplain. Thirteen plots showed Dq's above 5 cm and eleven plots showed Dq's below 5 cm. It was presumed that saplings in plots with a smaller Dq belonged to a younger cohort and could respond differently than those of larger Dq. Additionally, 5 cm is a relatively easy cutoff size for a person to visually assess in future management activities conducted on the floodplain.

Alternatively, BAI was examined across finer scales of initial size by grouping saplings within one of seven 3-cm diameter classes, beginning with 0-3.0 cm and ending with >18.1 cm. BAI and diameter increment were examined across classes within

treatments and years (2009, 2010, or both years) using Kruskal-Wallis tests (non-parametric one-way ANOVA; Proc Npar1way; SAS 2010).

Since only a fraction of the saplings currently alive in the understory will survive and grow into the upper canopy stratum, it is important to gain as clear an understanding as possible of growth of those individuals likely to do so in addition to overall plot growth. It was assumed that the largest saplings at the initiation of the study would display the lowest mortality rates and highest BAI in both treated and untreated conditions. The mean number of canopy trees (those greater than 25 cm dbh) within each study plot was determined at the beginning of the study. This was found to be approximately 19. In plots in which sub-plots were utilized, the largest $1/4^{th}$ of the sampled saplings were considered (6 plots). Thus, BAI of the 19 largest or top 25% of saplings in each plot was averaged across treatment type. A Wilcoxon ranked sum test of these 19 (or top 25%) saplings was performed to compare BAI across treatments, and Sign tests were used to examine BAI differences across year. Also, a Spearman Rank Correlation was performed was performed to examine basal area growth vs. initial size for these largest saplings in control and treatment groups.

Despite problems with using MRGR as a growth metric, relative growth was calculated to examine basic growth efficiency across size classes. Relative basal area increment rather than diameter increment was used:

$$RGR_{BA} = \ln(BA_2) - \ln(BA_1)/(t_2-t_1)$$

(South 1995)

where RG_{BAI} is the relative basal area increment growth (increase in basal area [cm^2] per unit of basal area [cm^2], while BA_1 and BA_2 were the basal areas of a sapling at the end of consecutive growing seasons. (T_2 - t_1) was always 1 because only single-year RGR_{BA} was examined. Relative growth values for both all treatment and all control saplings were

non-normal, and because of the large number of 0's (no growth), typical data transformations were ineffective. Thus, Ranked Sum tests were used to examine differences among treatments.

Analyses of Mortality

Mortality is an important process in stand development of both managed and unmanaged forests. Tree death is, of course, caused by a host of factors, including herbivory and disease, competition for light, water, and nutrients, and ecological perturbations such as drought, flooding, excessive sedimentation, wind, and fire, and all can be interrelated in a complex manner (Franklin et al. 1987). Tagged trees which died during the first year were not included in measures of growth. Those which died during the second year were included in first-year growth but not second-year growth or total growth. Average annual mortality rate was calculated as an exponential decay rate:

$$\text{Average annual mortality rate} = 1 - (S/N_0)^{(1/y)}$$

Where

S = number of survivors
N_0 = Original number of stems
Y = number of years between samples

(Runkle 2000)

This rate applied to the two years of the study combined. Sapling mortality rates of 2009 and 2010 are also reported individually. Mortality rates between treatments within single years or both years were tested with non-parametric Wilcoxon rank sum tests, as plot mortality rates were non-normal. To test whether mortality rates changed from 2009 to 2010 within treatment plots, within control plots, and as a whole, McNemar's Test (a non-parametric test) for correlated proportions was used (PROC FREQ; SAS 2010). McNemar's Test compares the observed data to the null expectation using a goodness-of-fit test. Two-year mean plot mortality rates (2008-2010) were normal, and initial mean

plot diameter (Dq) was regressed onto these rates (PROC REG; SAS 2010) to examine a potential correlation between size and survival.

Forest Survey of Broadneck Swamp Tract

Basis for and Design of Survey

Due to the large size of the Broadneck Swamp tract and the variability in baldcypress sapling occurrence and other forest characteristics discovered via the canopy-gap plots, it was decided that a larger forest-wide survey was needed to provide unbiased estimates of species composition and structural characteristics across a large portion of the tract and along potential hydrologic gradients. An additional goal was for the survey to provide a clearer understanding of spatial patterns in baldcypress sapling occurrence across the floodplain to aid managers in decisions regarding where to target canopy gap-creation restoration efforts. Spatial patterns in other forest characteristics, such as water tupelo diameter distributions, are also valuable as they may provide insight into variability which could be natural (due to growth differences) or related to timing of logging across the tract.

The study site for the forest-wide survey of Broadneck Swamp included backswamp regions as well as more elevated terrain all the way to the river itself and populated with various bottomland hardwood tree species. Fig.2-3 shows an outline of the entire sampled region within Broadneck Swamp. The survey was designed to capture the range in variation of woody species composition across the spatial extent of alluvial floodplain within the study area and to simultaneously capture the variation of woody species composition across the hydrologic gradient typically roughly perpendicular to major rivers in the southeastern U.S (see Wharton et al. 1982). A classic 10% forest cruise – that is, a survey intended to sample 10% of the very large study area (approx.

7.68 km^2), would have required time and resources far beyond the capacity of this project. The same was determined to be true for a 5% cruise. Thus, a different method was employed to determine the number of plots necessary to adequately capture the natural range of variability within a given level of error.

The sampling of canopy gap-creation treatment and control plots in August - November 2008 provided the opportunity to utilize backswamp forest characteristics (variability) in resolving the number of plots necessary. As these original plots were set up to specifically target baldcypress sapling clusters, they are not a truly random sample of floodplain forest, especially given the current survey's inclusion of riverside areas with distinctly different hydroperiod and soils (and therefore vegetation). However, given the size of the study area and the objectives of the survey, it was decided that this method provided the least biased method of resolving an adequate number of sampling units in the appropriate time frame.

Total plot basal area (BA) was used as the characteristic by which to determine number of plots needed, as the number of stems/plot was found to vary a great deal depending on floodplain location and the associated number of midstory Carolina ash stems. These midstory stems contribute relatively little to total basal area, which is steadier (though still variable) across hydrologic gradients.

The coefficient of variation (CV) of total plot BA was calculated and utilized in the equation:

$$N = [\{(t)*(CV)\}/A]^2$$

where A is the allowable error and t is the t-statistic for infinite degrees of freedom and a probability level (alpha) of choice (Avery and Burkhart 1983). Several allowable errors and probabilities were examined given the existing variation as viewed through canopy gap plots. The following were determined:

- For a 10% level of allowable error at a .9 alpha level – **17.4 (18) plots** are necessary
- For a 5% level of allowable error at a .9 alpha level – **69.5 (70) plots** are necessary
- For a 10% level of allowable error at a .95 alpha level – **24.6 (27)** plots are necessary
- For a 5% level of allowable error at a .95 alpha level – **98.6 (99)** plots are necessary

Another method was examined which utilized the percentage of mean basal area instead of the coefficient of variation:

- For a level of error of +/- 6% of the mean BA, **71.3 (72) plots** are needed
- For a level of error of +/- 5% of the mean BA, **102.7 (103) plots** are needed

Thus, it can be seen that, given the level of BA variability of existing plots, a distinction exists in what would be required for a certain level of accuracy. Approximately 100 plots provides only a somewhat minimal increase in the accuracy guarantee over establishing approximately 70 plots. Thus, an initial decision was made to use 70 plots for the survey. It should be reiterated that the above calculations are for a population represented by backswamp forest species/characteristics only, and that inclusion of bottomland hardwood areas closer to the river in these 70 plots led to an increase in overall BA variability so that allowable error goals were not likely met, though were probably still close (see RESULTS). Soil series boundaries were included in the map below (Fig. 2-3) to illustrate the number of plots established in the Chewacla series, a bottomland hardwood soil closer to the river which is generally higher in elevation, drier, and slightly more coarsely textured (NRCS 2009).

Initially, 7 linear transects were laid out with starting points at evenly spaced intervals along the Roanoke River's northern bank within the area of study. Along each transect, 10 plots were established at an even interval based on the total distance of the transect from the riverbank to the Town Swamp access road, which acts as the northern

boundary of the study area (Fig. 1-1). In order to sample along the predicted hydrologic gradient as closely as possible, transects were not necessarily parallel to one another, but rather established so as to produce a 90-degree angle with the river's edge at the point of transect origin. Due to natural bends in the river and the width of the floodplain, this led to large areas with few plots and other areas with an abundance of plots. Also, one transect actually crossed several others. Several plots in areas of over-abundance were moved prior to sampling to form a lighter semi-transect (6 plots) along the eastern side of the study area roughly parallel with Black Gut (eastern boundary of the study area) but still perpendicular to the river (Fig. 2-3). This design of transects successfully avoided sampling close to any of the several natural and man-made inlet canals connected to the river in a parallel fashion. Transects did cut across several such inlet canals in a roughly perpendicular manner (Fig. 2-3).

Following data collection of the initial 70 plots, more time and resources were available than initially anticipated. Thus, to reach higher levels of accuracy, 30 more plots were established. One transect of 10 plots (transect 2, Fig. 2-3) was set up in a similar manner to those described above, except its starting point was located in between two transects which diverged due to a natural bend in the river and therefore

Fig. 2-3: Map of survey plot transect layout across the study site (outlined in red). Plot point centers are yellow dots, with the beginning of each transect noted by a white number. Brown lines indicate soil series boundaries for the region as determined via NRCS Soil Survey data (NRCS 2009). Blue lines are small natural or man-made inlet canals within the study site.

caused a enlarged un-sampled region between them. This new transect could not be established exactly halfway between transects 1 and 3 because of the presence of a man-made inlet canal, so it was offset by placing its starting point halfway (distance) between the inlet canal's mouth and the starting point of transect 3.

The remaining twenty additional plots were established along existing transects 3 and 5 (10 more on each) exactly halfway between existing plots. This was done in order to sample to a greater level of precision along the hydrologic gradient from river to backswamp, and therefore gain a clearer understanding of how vegetation changes in relation to potentially slight differences in hydrology.

All plot center points were marked with 1.27 cm diameter PVC poles and adjacent flagging for visibility. PVC markers at all plots were painted for visibility for possible repeat surveys.

Survey Plot Measurements

Forest-wide survey plots were 456 m^2 in area, which is exactly the same as treatment and control plots from the canopy gap creation experiment. This means each plot had a radius of 12.05 m. This can be compared to a typical forestry $1/10^{th}$ acre plot, which has a radius of 11.35 m. In each plot, all stems greater than or equal to 3 cm dbh were measured for diameter and identified to species. The same protocol as canopy gap creation plots regarding measurement of with and without butt swell was followed. Stems were considered "in" if they were rooted inside the plot. If a stem straddled the plot boundary line, it was considered "in" if the rough center point of where its bole made contact with the ground was inside the boundary. Of the 102 total, 24 plots were situated on soil series other than Wehadkee Loam, the highly organic soil associated with deep, prolonged flooding in the backswamp (NRCS 2009). These 24 plots tended to host more tree species and trees less adapted to such prolonged flooding as baldcypress and water

tupelo. They were analyzed together with all backswamp plots, and then subsequently removed and each group analyzed separately.

Species Importance Values

Forest-wide survey species' diameters were averaged by species and soil type and were converted to basal area/ha and averaged similarly. Species importance values were determined in a manner similar to that of species from canopy gap experiment plots, and are reported below. Since this survey represents a non-biased examination of the tract, these importance values provide a much more accurate indication of forest composition and structure of the entire floodplain.

Sapling Ages

A knowledge of the range of sapling ages being subjected to release would help provide an understanding of the future potential of canopy release as a management tool in other stands with regeneration of similar or differing ages. In addition, sapling ages may show a relationship with size (dbh). In April 2010, three saplings from each plot were cut at 7.6 cm above the ground and a slab cut from the bottom of the tree. Slabs were air-dried for seven days and then machine-sanded with progressively finer-grit sandpaper (80-320). Two coats of linseed oil were then applied to each slab to improve ring visibility. Four lines were drawn from the center (pith) of the slab at 90 degree angles, and rings were counted with the aid of a 10-30x power microscope. A ring count was performed in each of the four sections of each slab in order to account for merging/missing rings and aggregations of darkened cells which appeared like rings but did not extend all the way around the slab. Since slabs were taken from nearly ground-level, it was assumed that ring counts represented actual ages of the tree.

Three slabs were obtained from 22 of the 24 plots (n=66) – one each from a small (<6 cm), medium (6.1-10 cm) and large (> 10 cm) dbh class. Saplings were cut nearby

(within 20 m) plots, and care was taken to avoid removing saplings near enough and/or tall enough to compete for light with saplings actually inside any of the plots. Areas near several plots did not contain saplings of sufficient sizes to support the above distribution. Areas near six plots contained saplings which were too small, and so distributions were shifted slightly downward. A sapling smaller than 10 cm could not be found nearby one plot, and a slab from one plot was thrown out because rings were too faint to count. See Appendix B for all initial sizes and sectional ring counts.

In many slabs, rings which would merge into other rings or blurry "rings" near the pith caused sectional counts which were different from one another to varying degrees. Ring merging was especially prevalent among the most recent outer rings. In some slabs, an individual section could not be utilized because of ring faintness or rotting or scarring. Most slabs varied 0-4 years among sections, but two slabs showed 5-year variance, two showed 6-year variance, and 1 slab varied by fully 13 years. Slabs with more than four years of variance were removed, and the median of the remaining slabs was used to provide a final slab age. Where the median was a 0.5 value, age was rounded to the mode (usually down). When all four sections were of different values, median was rounded down. Ring counting was being done only to provide a general range in sapling ages, so error associated with counts was considered acceptable. However, an age-size (dbh, n=61) regression was performed (PROC REG; SAS 2010) on slabs using median age values to determine if a basic relationship existed.

Sapling ages were compared to Roanoke River flows at Roanoke Rapids Dam upstream of the study site. These flows are strongly correlated with backswamp flooding (Pearsall et al. 2005), and thus are used to examine potential periods of sapling establishment. Daily mean flows were obtained from USGS records for the period 1912 – 2008 (USGS 2010), and growing season (March 1 – August 31) periods closely examined.

CHAPTER 3 – RESULTS

Sapling Ages

Sapling ages varied between 12 and 38 years (Appendix B). Overall mean age was approximately 22, but variability produced a standard deviation of +/- 6.3 years. There was more age variation within plot regions than expected (average range: 6.05 years). However, of the 21 plots with more than one measured slab, 11 supported saplings of a range less than 5 years. Of the 22 total, 9 supported saplings fully within the 20-29 year-old age range. If plots with saplings entirely below 20 years-old are removed, the mean age is nearly 24. Saplings from 24 – 26 years old would have established in the period 1984 – 1986. Five plots supported saplings 12-18 years old. This puts germination dates for this younger class between 1992 and 1998.

It appears, based on examination of Roanoke River flows during possible dates of establishment, that there may be four sapling cohorts in the study area. Fig. 3-1 shows Roanoke River discharge for periods 1980-1983, 1984-1987, 1992-1996, and 1998-2003. It is known that backswamp flooding begins to occur at multiple consecutive days of at least 326 m^3/sec daily mean discharge (Pearsall et al. 2005; J. Richter, personal communication, Aug. 2008). The years 1980 and 1982-1984 were generally marked by long periods of flow above this threshold in the spring and early summer (germination and establishment period). The number of days between March 1 and August 1 above 326 m^3/sec in 1980 was 58 (of 183 total). The period 1982-1984 produced flows of at least 326 m^3/sec over 42, 93, and 103 days, respectively. In 1981, however, conditions were much drier, and there were no days in which flow exceeded the above threshold. Saplings established in 1981 would be 29 years old by 2010. This perhaps accounts for the older counts recorded among various slabs.

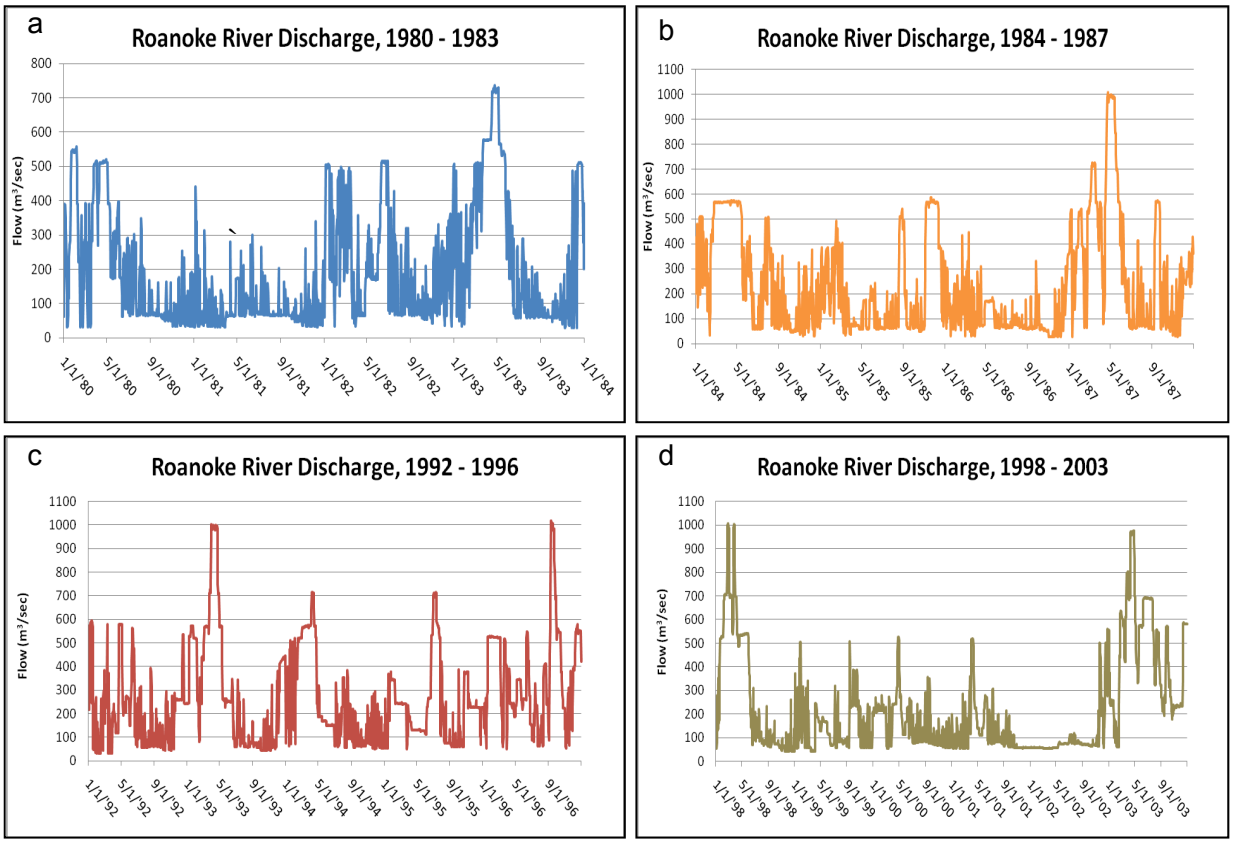

Fig. 3-1: Roanoke River discharge at Roanoke Rapids Dam for four different periods. Backswamp areas typical of mass baldcypress sapling establishment tend to flood after multiple consecutive days of flows at 326 m^3/sec and greater.

The years 1984 and 1985 were comparably dry during the growing season, showing 15 and 0 days of mean flow >326 m^3/sec during the growing season, respectively (Fig. 3-1b). Extended periods of backswamp flooding clearly occurred in the dormant season of 1985 and 1986, two consecutive years of low flows during the active growing season that may have been adequate for a majority of the study site's saplings to establish.

The early 1990's were generally characterized by 35 or more days of >326 m^3/sec daily mean flows. Though it only experienced 39 total growing season days of flood-level flows, 1995 was not likely conducive to seedling survival because most of those days

came in a single late June-late July flood event with an average daily mean flow of nearly 600 m^3/sec (Fig. 3-1c). However, 1992, though it experienced only slightly fewer growing season flood-level flows (36), was likely more conducive to permanent seedling establishment because flooding was more spread out and therefore more pulse-like (Fig. 3-1c). Three high-flow periods of 10-14 days were separated by 30-44 day interludes of lower flow. As noted previously, baldcypress seedlings have been shown to survive 30-45 days of overtopping in clear water (Souther and Shaffer 2000), though death is probably somewhat quicker than this in darkened water and beneath a canopy. It is quite possible that saplings with a median age of 17-20 years-old actually established during the 1992 growing season, though the following dormant season and 1993 growing season brought extensive flooding. This may account for the relatively small number of slabs (12 of 61) between 17-21 years old.

Alternatively, a relatively long drought occurred between 1999 and early 2003 in which four consecutive growing seasons experienced very little flooding (Fig. 3-1d). This period likely accounts for the establishment of the youngest cohort found on the floodplain (saplings from plots 3A, 6A, 3B, 5B, 6B; Appendix B). The year 2003 brought the most intense floods on record, thus likely wiping out 2002's and possibly 2001 and 2000's established cohorts.

An age-size regression showed a significant positive relationship ($p < .0001$), but the R^2 value was only .26 (Fig. 3-2). Thus, there is considerable variation – for both smaller and larger individuals in a sapling's age at a given diameter, and diameter does not explain much of the variation in age.

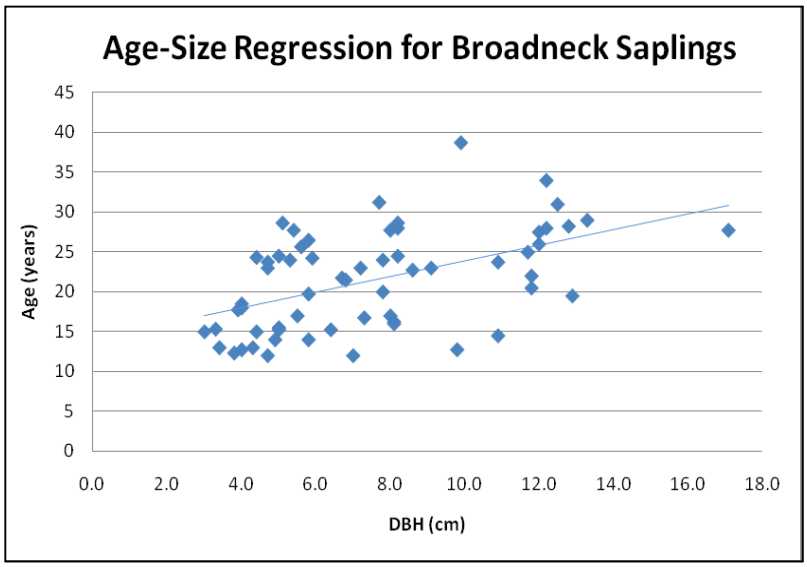

Fig. 3-2: Age-size relationship for the median age (of four sectional ring counts) of saplings cut just outside treatment and control canopy-gap experiment plots. The relationship was significant (p <.0001), and is defined by the equation: age = .983(dbh) + 13.9.

General Canopy Gap Experiment Plot Characteristics

Importance Values for all species encountered in canopy gap experiment plots are provided in Appendix C. Artificial canopy gap plots were dominated in the overstory by water tupelo, which made up nearly 90% of the basal area and held the highest importance value at 44.4 (Appendix C). Overstory tupelo averaged 43.7 cm (Dq) over all plots. Water tupelo's diameter distribution can be seen in Fig. 3-3. The very dense 0-4.9 and 5-9.9 cm diameter classes are highly skewed by small Carolina ash stems. The other classes are composed mostly of water tupelo, and form a unimodal distributional shape. This suggests that the Broadneck Swamp forest canopy is generally even-aged (Lorimer and Krug 1983). Baldcypress adults (>25 cm) were present in only 2 of the 24 plots, and held an importance value of only 1.79. When saplings <25 cm are included, the species' importance value jumps to 35.9, but plots were intentionally established to capture groups of saplings, and so this value is biased. Total density of adult baldcypress across the

floodplain is reported in results of the forest-wide survey below. Among canopy-gap plots, Carolina ash density was quite variable.

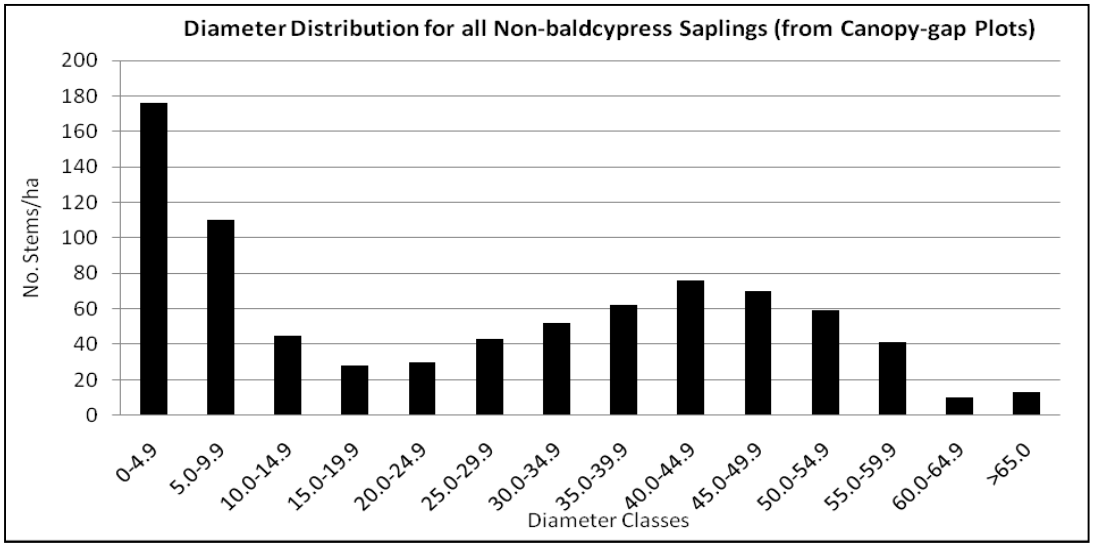

Figure 3-3: The diameter distribution of all non-baldcypress saplings from all canopy-gap study plots. Large numbers in the lowest diameter classes are due to an abundance of small Carolina ash stems. Aside from this species, water tupelo comprised the vast majority of stems, and its distribution takes a generally unimodal shape.

Across all plots, it was the most abundant species in terms of stems/ha, but its importance value was 11.2, and total Carolina ash basal area was only 0.06% of that of all species. It ranged in size from 1 to 18.5 cm, but Dq was 6.9 cm.

The vast majority of Carolina ash were 0 – 9.9 cm (Fig. 3-3). At least 1 stem existed in every plot. Plot density ranged from 1 - 38 stems. These large numbers of small stems are important because they are an indicator of a significant competitor of baldcypress within relatively shallowly-flooded transition zones of the backswamp. In some transitional zones of other parts of the swamp, Carolina ash was very dense and excluded baldcypress entirely (see Forest-wide Survey results).

Baldcypress Sapling Characteristics

Overall, 1215 baldcypress saplings were tagged initially, 647 in treatment plots and 568 in control plots. Saplings ranged in initial size from 0.3 to 24.9 cm in diameter, with mean plot Dq ranging from 1.7 to 11.3 cm. Overall Dq was 6.2 cm (Appendix C). Appendix A shows matching sapling structural data on all paired plots. Coefficients of variation of sapling size within plots averaged 60.3%, indicating that saplings ranged widely in size within most plots.

In contrast to what was expected, within-plot initial sapling size variation in plots with smaller mean diameters (<5 cm) was not lower than in plots with larger mean diameters (>5 cm). In fact, the reverse was true – coefficients of variation in plots with larger saplings were significantly smaller than those of plots with smaller saplings (46.5% vs. 54.3%; $p < 0.017$). Though plots with large saplings had a slightly larger overall range in size, this trend in within-plot variation suggests that the results of competitive exclusion (size differential and relative dominance of some saplings) have already begun by the time these small sizes and densities are reached. Since the median age of the youngest plot was approximately 12-13, it is clear that saplings growing in these densities have established larger and smaller individuals – and likely winners and losers in the race to the canopy (see Growth results below) – by this early age.

Baldcypress sapling density ranged from 23 – 214 stems/plot, though the 6 densest plots were estimated from sub-plot densities (Appendix A). This corresponds to 504 – 4692 stems/ha, which are very high densities. Of course, because saplings occurred in isolated bands/clusters and canopy-gap study plots targeted these clusters in a biased manner, these densities do not represent the vast majority of backswamp area. A more spatially accurate description of across-floodplain abundance of baldcypress saplings can be found in the Forest-wide Survey Results.

Since plots were paired based on mean initial sapling size alone, the difference between paired plots in that characteristic was relatively small – a difference of 0.435 cm (~8% of the overall mean). However, average differences in other important plot characteristics, such as initial total sapling basal area (1111 cm^2, ~50% of mean), total canopy tree basal area (0.759 m^2, ~25% of mean), and canopy tree density (122.4 stems/ha, ~28% of mean), were higher. These initial differences between plots are a potential source of error among paired plot comparisons. However, analysis done between entire treatment types is not subject to such error.

Results of Herbicide Treatment and PAI

The girdling and herbicide (*Habitat*) treatment of all non-baldcypress woody stems in the 12 treatment plots generally produced the desired/expected conditions. By Spring 2009, the majority of treated stems of all size classes and species (non-baldcypress) were dead or severely stressed to the point that they did not produce leaves. Many large water tupelos leafed out initially but quickly dropped these leaves. The death and defoliation of most trees in the plots clearly increased light available to saplings on the forest floor by the 2009 growing season. However, at least 1 or 2 large canopy trees survived through the 2009 growing season in every treatment plot, with most plots harboring 6-9 survivors with some or a great deal of their foliage. It is unclear what factors led to the survival of individual tupelo, but, due to their size, these trees obviously produced considerably more shade than would have existed with their complete defoliation. Thus, small amounts of shade covered treatment plots during the first growing season. This, along with floodplain water levels during the summer of 2009 prevented a reassessment of PAI and light levels during that time.

Survivors (any trees hanging on to any amount of foliage) were re-treated in December 2009. It was discovered during re-treatment that most survivors that had been

holding some leaves during the previous growing season were nearly dead, and only small fractions of the cambium and outer trunk held living tissue and active sapwood. By the early growing season of 2010, only a handful of trees across all treated plots held any leaves, and these trees held very minimal amounts of leaves.

An initial worry at the outset of the treatment was whether Imazapyr (*Habitat*'s active ingredient) applied to canopy trees would "leak" from their roots into the surrounding soil substrate and potentially cause death or stress to nearby baldcypress saplings. Although this has been shown to occur in treated nitrogen-fixing legumes, such as mesquite (Nature Conservancy 2001) and other plants (see Chapter 2), it did not appear to occur over the two years in this study, even though there was high sapling mortality rates in some plots which are likely due to other factors (see below).

In 2008, light levels (DIFN) in plots ranged from 0.5 – 2.5% full sun. Treatment plot DIFN averaged 0.011 ± 0.006 (1.1 ± 0.6% full sun) prior to treatment, while control plot DIFN averaged 0.013 ± 0.004 (1.3 ± 0.4% full sun). PAI's ranged from 4.41 to 6.26, with treatment plots averaging 5.35 ± 0.5 and control plots averaging 5.08 ± 0.29. Several large storms affected the study area during the 2-year interval between PAI/DIFN measurements. Treatment plots were affected by these storms to a far greater degree as large, dead water tupelo snapped near breast height or large limbs and tops broke out. This was especially prevalent among trees already hollow prior to treatment. These falling trees (Fig. 3-4) killed some saplings, but did minimal damage overall.

Leaf area and light levels in August 2010 were somewhat similar in control plots and far different in treatment plots. Control plots ranged in PAI from 3.59 - 5.55 with an overall mean of 4.72 ± 0.56. Control plot DIFN ranged from .008 to 0.47 and averaged .02 ± .01 (2% ± 1% full sun). Thus, though mean PAI was only 0.36 lower and mean light levels only 0.7% higher in control plots in 2010, this represented a significant

Fig. 3-4: Fallen water tupelo trees in a treatment plot only 19 months following girdling and herbicide application. Most treated plots had 2-5 fallen canopy trees at this point.

difference from original conditions (p=0.005 and 0.009, respectively). It is unclear what led to these changes over the two-year time frame. Storms, as noted before, minimally affected some of the control plots, blowing down small limbs from some canopy trees. In one plot an entire large overstory tree fell and opened up some of the canopy. Given the small changes involved, this could be a reasonable explanation. Also, PAI measurements were conducted from August 1- August 16 in 2009, and from August 17 – August 23 in 2010. Tupelo trees were in the very early stages of leaf fall in both years, and the later sampling date in 2010 could have meant fewer leaves in the canopy and thus slightly lower PAI and slightly higher DIFN.

In 2010, treatment plots ranged in PAI from 2.09 – 3.85, actually overlapping with control PAI's. DIFN's ranged from 0.061 - 0.264, or 6.1% - 26.4% full sun. Means were 2.93 ± 0.56 (PAI) and 0.169 ± 0.65 (DIFN), both strongly significantly different from pre-treatment means. Thus, on average, treatment increased light levels within plots by 15.7% ± 6.1%. As a comparison, control plot light levels were 0.7 ± 0.8% higher in

2010. Photos below show treatment plot conditions in 2009 and 2010 (Fig. 3-5). See Appendix D for all pre- and post-treatment PAI/light level data.

Fig. 3-5: Undisturbed Broadneck Swamp canopy looking up from level of saplings, July 2008 (a) and saplings growing in midstory beneath artificial canopy gap, August 2010 (b)

Baldcypress Sapling Growth

Growth Caveats

Two important issues should be discussed before baldcypress sapling growth results are presented. The first issue is the accuracy of recorded growth of large saplings (larger than 8 cm) as measured with a typical forester's d-tape. A subset of 27 banded saplings was measured with a d-tape directly below the mounted steel dendrometer band to compare these d-tape measurements with precise band readings. This analysis showed d-tape measurements over two years are relatively accurate, with the mean of the absolute value of difference being 0.127 ± 0.19 cm. Overall two-year mean diameter increment of saplings larger than 8 cm was 0.42 ± 0.48 cm. The large variability in both the tape vs. band difference and the mean growth means that tape error may overlap with growth on some individuals, especially those of low growth. Effects are likely to diminish over time as most of the error seems to be associated with smaller levels of growth (Fig. 3-7).

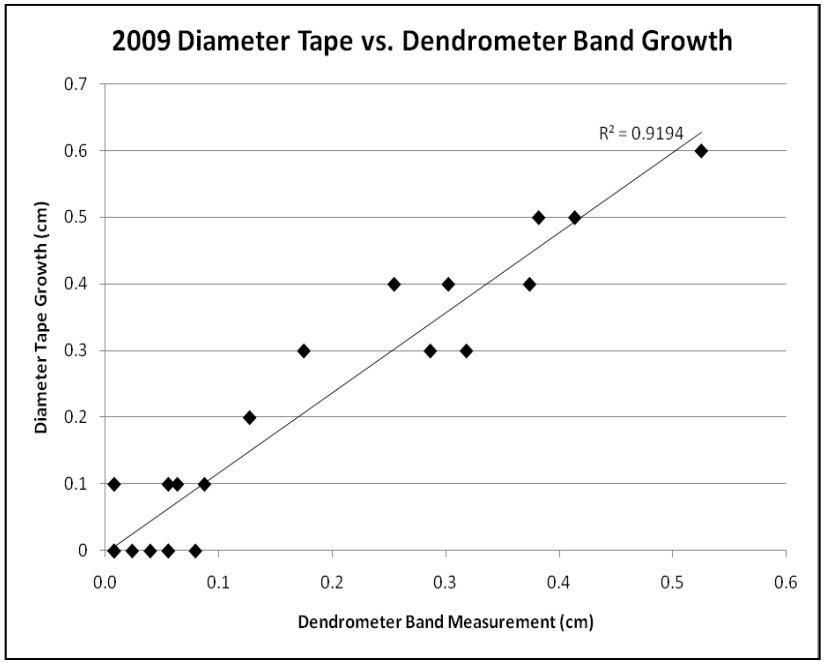

Fig.3-6: Diameter tape measurements appear to be strongly correlated with precise dendrometer band measurements for saplings over 8 cm dbh.

A second potential issue arises from error associated with caliper measurement. To determine average caliper error, one plot (a treatment plot) was randomly selected and all saplings measured a second time in August 2009. The 95% confidence interval for difference in diameter per individual was found to be (0.029, 0.043 cm). This is less error than that associated with the diameter tape measurements on larger saplings, and is smaller than average sapling growth in treatment plots. However, it is not smaller than average sapling growth in control plots. This simply means that 1st-year results from control plots must be viewed with caution. For the most part, total two-year growth increased beyond this 0.029 - 0.043 cm level.

Baldcypress Sapling Growth

Baldcypress saplings responded well to treatment, with BA increasing an average of 6.97 ± 7.3 cm^2 over two years and ranging from 0 cm^2 to 52.03 cm^2 – nearly eight

times more than control saplings, which increased .88 ± 1.79 cm^2 over two years and ranged from 0 – 16.04 cm^2.

In the first post-treatment growing season (2009), treatment saplings increased nearly five times more in basal area than control saplings, and the difference was significant regardless of whether plot means were averaged or all saplings were grouped by treatment (Table 3-1; $p < 0.0001$). Range of BA increase in each treatment type was relatively wide, with saplings beneath gaps ranging from 0 to 23.7 cm^2, and those in control plots ranging from 0 to 13.1 cm^2.

Variability in BA change within both treatments and plots was high, primarily due to the large number of saplings showing very low or zero increase. The number of saplings showing no increase in 2009 was strongly different between treatments. In treatment plots, 13.6% (n = 647) of saplings did not grow at all in year 1. Nearly 42% (n = 568) of control saplings showed zero growth, however. Rates of zero growth were similar (13.2% vs. 14.3%) between small (<5 cm) and larger (>5 cm) saplings in treatment plots, and in control plots larger saplings actually showed higher zero-growth rates (53.8% vs. 31.9%). This is contrary to what might be expected, and suggests that intra-specific competition is not the sole determinant of basal area increase on these long-suppressed saplings.

In year 2 (2010), the number of saplings showing zero growth had climbed to 47% in control plots and dropped to 3.4% in treatment plots. Overall sapling growth increased to 2.65 ± 4.14 cm^2, largely driven by a 90% increase in treatment sapling growth (Table 3-1). Control saplings, on the other hand, averaged 0.4 ± 0.93 cm^2 in growth, which was nearly the same as the previous year and significantly less than treatment saplings (Table 3-1).

GROWTH in CM^2 ± 1 S.D.	TREATMENT	CONTROL	OVERALL
All Saplings 1st Year	2.38 ± 2.93[a, I]	0.49 ± 1.25[b, I]	1.49 ± 2.48[c, I]
Plot Averages 1st Year	2.74 ± 1.26	0.59 ± 0.48	1.67 ± 1.43
All Saplings 2nd Year	4.53 ± 4.79[a, II]	0.40 ± 0.93[b, I]	2.65 ± 4.14[c, II]
Plot Averages 2nd Year	4.69 ± 1.79	0.39 ± 0.23	2.54 ± 2.53
All Saplings Both Years	6.97 ± 7.34[a]	0.88 ± 1.79[b]	4.19 ± 6.32[c]

Table 3-1: Basal area growth of saplings across 1st, 2nd, and both years of study and grouped by treatment or treatment and plot. Differing letters denote significant differences between treatments within year. Differing Roman numerals denote significant differences within treatment between 2009 and 2010.

A paired t-test among paired plots also showed that treatment plots outgrew (in terms of BAI) control plots with saplings of similar Dq in a strongly significant fashion in all time period combinations (2008, 2009, and both years all $p < 0.0001$). Figure 3-8 shows the differences in paired plot mean BAI across initial diameter as well as the differences in paired plot mean diameter increment across initial diameter (Dq). This illustrates the difference in analyzing with raw diameter growth and raw basal area increment, as the relationships were essentially polar opposites and both significant (R^2 = 0.49 and 0.54; BAI $p = 0.008$, Diameter Increment $p = 0.009$).

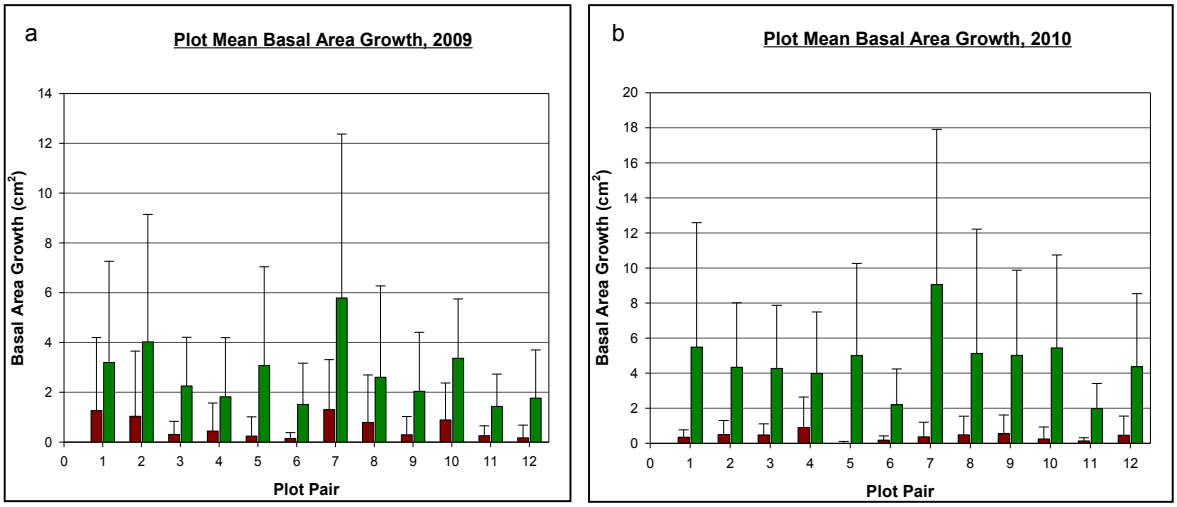

Fig.3-7: Plot mean basal area growth of saplings for the 2009 (a) and 2010 (b) growing seasons, by plot pair (+/- 1 SD). Green bars are treatment plot means. Maroon bars are control plot means. Note the slight difference in scale between a and b.

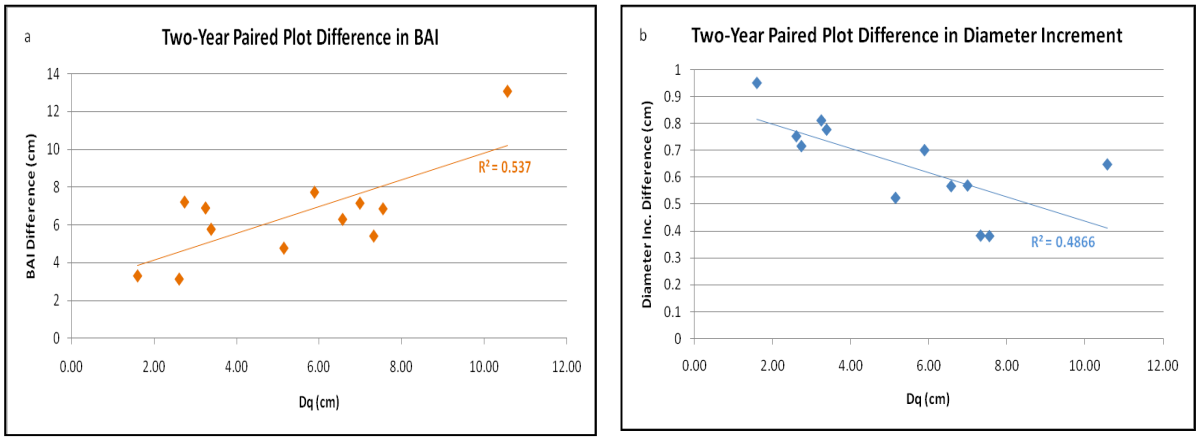

Fig. 3-8: Differences in two-year paired-plot mean basal area increment (a) and diameter increment (b) plotted across initial quadratic mean diameter.

In year 1, saplings initially larger than 5 cm put on more than twice the basal area growth of those less than 5 cm (Table 3-2). A similar pattern existed within both treatment and control groups, but with greater growth for treatment and lower growth for control (Table 3-2). Large saplings in control plots did not show significantly greater growth than smaller saplings, primarily because of very high variability among larger saplings.

Growth in cm^2 ± 1 S.D.	Control	Treatment	Overall
1st Year (2009) <5 cm	$1.43 \pm 1.5^{a,I}$	$0.28 \pm 0.93^{a,I}$	0.92 ± 1.4^{a}
1st Year (2009) >5 cm	$3.97 \pm 3.9^{b,I}$	$0.77 \pm 1.52^{a,I}$	2.34 ± 3.34^{b}
2nd Year (2010) <5 cm	$2.55 \pm 2.4^{a,II}$	$0.26 \pm 0.46^{a,I}$	1.55 ± 2.1^{a}
2nd Year (2010) >5 cm	$7.73 \pm 5.9^{b,II}$	$0.61 \pm 1.29^{b,I}$	4.27 ± 5.59^{b}
Both Years (2008-2010) <5 cm	4.08 ± 4.0^{a}	0.58 ± 1.55^{a}	2.56 ± 3.64^{a}
Both Years (2008-2010) >5 cm	11.61 ± 8.9^{b}	1.27 ± 2.01^{a}	6.59 ± 8.35^{b}

Table 3-2: Mean basal area growth of saplings initially less than or greater than 5 cm diameter across 1st, 2nd, and both years of study and grouped by treatment or treatment and plot. Differing letters denote significant differences between size classes within year and treatment. Differing Roman numerals denote significant differences between 2009 and 2010.

In looking at radial growth in relation to finer scales of initial size, there again seemed to be a positive relationship among treatment saplings, and no relationship among control saplings (Fig. 3-9). However, sample sizes in the three largest 3-cm diameter classes were small (1-7 stems). Nonetheless, Kruskal-Wallis tests confirmed that, both in 2009 and 2010, control sapling growth did not differ across these diameter classes (just barely non-significant at p=.0571), while differences across treatment sapling diameters were strongly significant (p <.0001).

Fig. 3-9 shows that most individual treatment diameter classes were different from each other, according to multiple Wilcoxon rank sum tests.

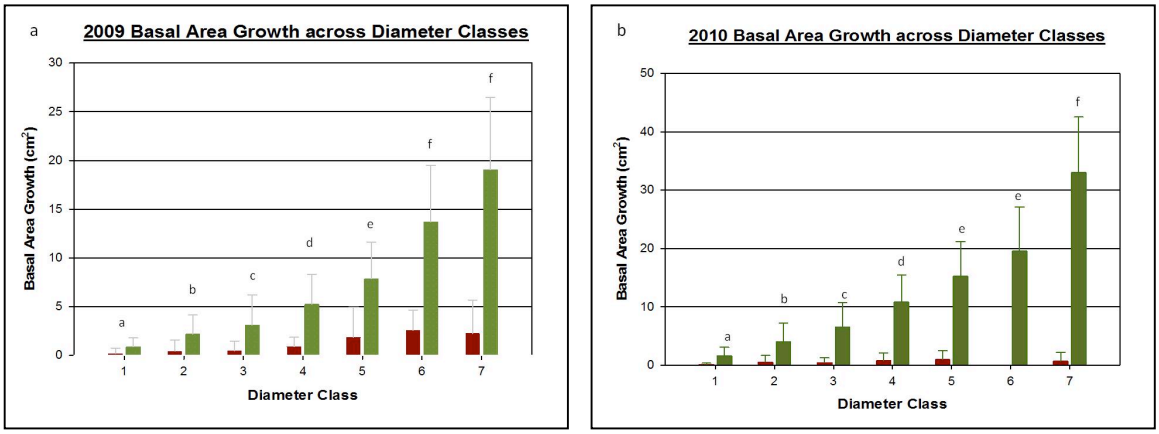

Fig.3-9: Basal area growth across initial diameter classes for the 1st and 2nd growing season – 2009 (a) and 2010 (b). Green represents treatment plot saplings and maroon represents control plot saplings. Error bars represent +/- 1 standard deviation. Diameter classes are as follows: ***1*** *= 0 – 3 cm;* ***2*** *= 3.1 – 6 cm;* ***3*** *= 6.1 – 9 cm;* ***4*** *= 9.1 – 12 cm;* ***5*** *= 12.1 – 15 cm;* ***6*** *= 15.1 – 18 cm;* ***7*** *= >18 cm. Different letters represent significant differences in growth among treatment means. Neither 2009 nor 2010 control means were significantly different (p= 0.051 and 0.102, respectively).*

Basal area growth of the initially largest saplings in each plot (top 19 or top 25%) also was also far higher in treatment plots than control (Table 3-3) for both years following release, and the growth of these larger saplings was clearly higher than growth of all saplings combined (Table 3-1) and all saplings larger than 5 cm (Table 3-2). The 1st-year difference between treatment and control saplings was strongly significant (p <.0001), and these largest treatment saplings widened the growth difference further in

year 2. In 2010, large control saplings put on less growth than in 2009, paralleling the overall control trend (Table 3-3).

Though larger saplings generally grew more than smaller ones beneath unbroken canopy (Tables 3-2 and 3-3), the weak relationship with initial diameter (Figs. 3-9; 3-10) reinforces the notion that size may have only minimal influence on growth after many years of suppression.

GROWTH in CM^2 +/- 1 st. dev.	TREATMENT	CONTROL	OVERALL
1st Year (2009)	$6.26 \pm 4.09^{a,I}$	$1.00 \pm 0.92^{b,I}$	$3.63 \pm 3.95^{c,I}$
2nd Year (2010)	$10.18 \pm 5.28^{a,II}$	$0.73 \pm 0.49^{b,I}$	$5.46 \pm 6.06^{c,II}$
Both Years (2008-2010)	16.22 ± 9.06^{a}	1.63 ± 1.81^{b}	8.92 ± 9.77^{c}

Table 3-3: Mean basal area growth of the 19 largest saplings (or top 25% for plots with subplots) across 1st, 2nd, and both years of study and grouped by treatment or treatment and plot. Differing letters indicate significance between treatment groupings. Differing Roman numerals denote significant differences between 2009 and 2010.

Mean basal area growth of the 19 largest saplings from each plot (or top 25% from plots with subplots) showed a strongly significant correlation with initial diameter for treatment plots in both 2009 and 2010 ($p < 0.0001$ for both; Fig. 3-10 a2 and b2). Growth from these largest saplings was not significantly correlated to initial diameter for control saplings in 2009 ($p = 0.679$), but was significant in 2010 ($p = 0.011$). The 2010 r_s was -.178, however, indicating that growth tends to decrease as initial diameter increases, and the relationship was weak.

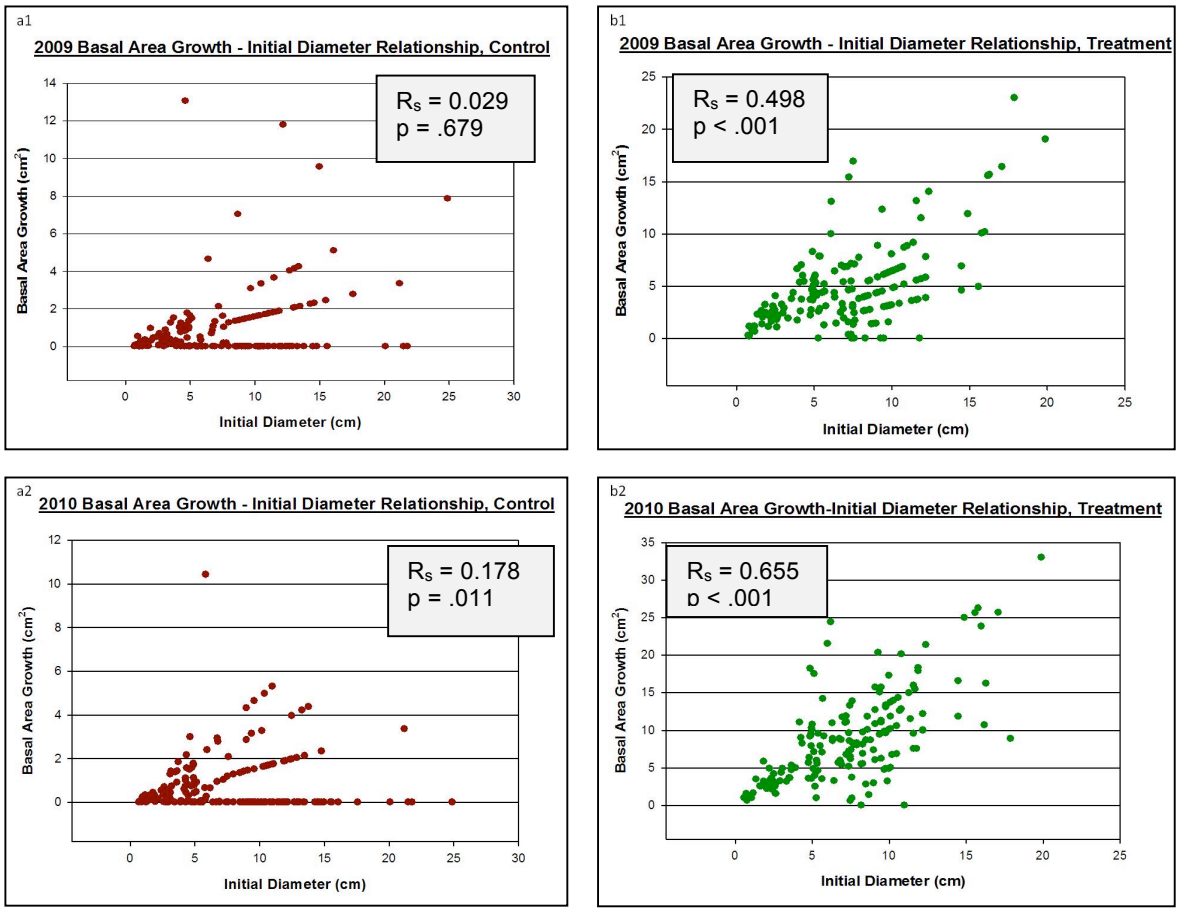

Fig.3-10: Scatter plots of basal area growth of the largest 19 saplings from all control plots (maroon a1, b1) and treatment plots (green a2, b2) relative to initial diameter for 2009 and 2010. The 2009 control regression was significant ($p = 0.0167$) with a weak R^2 of .049, and the 2009 treatment regression was also significant ($p < 0.0001$) with an R^2 of .36.

The relationship between sapling diameter and two-year growth within plots was also examined with a scatterplot of plot Spearman correlations (Fig. 3-11). Treatment plots had consistently stronger initial size-growth relationships than control plots, though r_s values remained stable across mean plot diameter. Control r_s values tended to drop as mean plot diameter increased. These results are an illustration of what appears to be a lack of intraspecific competition among sub-canopy saplings in clusters with larger mean diameters – *i.e.* those subjected to a longer period of suppression. Despite the fact that the largest 19 sub-canopy saplings are growing more than the overall sub-canopy average

(1.63 cm^2 vs. 0.88 cm^2), there is a loss of size advantage in the larger clusters as almost all saplings slow in growth considerably. On the other hand, release seems to have re-initiated the advantage for being large relative to neighbors across the board within treatment plots (Fig. 3-9, Fig. 3-11).

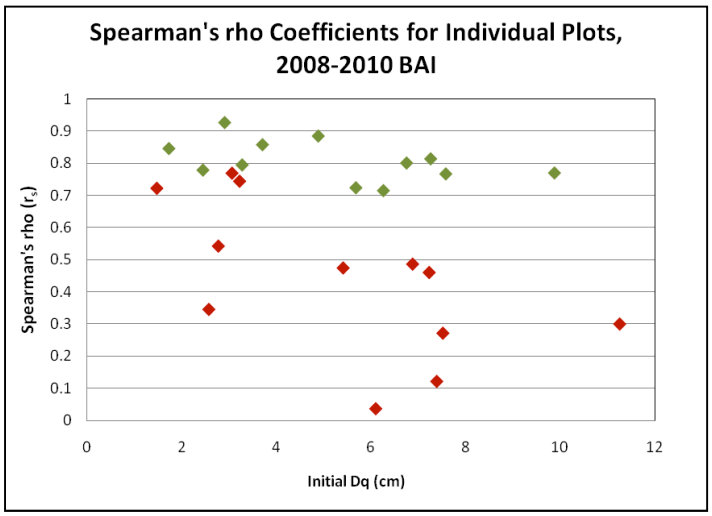

Fig. 3-11: Spearman's Correlation Coefficients (r_s) for individual plots between two-year basal area increment and initial mean plot diameter. Green diamonds represent treatment plots; maroon diamonds represent control plots.

Growth Across Viability Classes

Initial viability classes showed a high degree of variability in basal area growth. Table 3-4 shows that, unsurprisingly, for both control and treatment saplings, the subjectively "healthiest" saplings (viability classes 0 and 1) grew significantly more than weaker/dying trees (viability classes 2 and 3). Saplings with a viability class of three – those with some level of previous beaver damage – were not significantly different than viability classes 1 or 2, but probably would have been but for high variability due to small sample size (Table 3-4). High variability was present in all classes of both treatments, however. The highest viability class showed by far the most growth, putting on over twice the basal area of the next viability class both in treatment and control.

BA Growth (cm^2)	VIABCLASS	Control	Treatment
1st Year	0	1.18 +/- 2.13 a, I	6.18 +/- 4.52 a, I
	1	0.44 +/- .57 b, I	2.5 +/- 2.14 b, I
	2	0.12 +/- .26 c, I	0.61 +/- .91 c, I
	3	0.04 +/- .1 bc, I	0.54 +/- .45 bc, I
2nd Year	0	0.96 +/- 1.28 a, I	10.84 +/- 6.49 a, II
	1	0.32 +/- .81 b, I	4.60 +/- 3.64 b, II
	2	0.09 +/- .48 c, I	1.69 +/- 2.34 c, II
	3	0.08 +/- .19 c, I	0.92 +/- .58 c, I
Both Years	0	1.94 +/- 2.57 a	16.96 +/- 9.94 a
	1	0.76 +/- 1.56 b	7.16 +/- 5.48 b
	2	0.20 +/- .63 c	2.31 +/- 2.91 c
	3	0.12 +/- .29 c	1.20 +/- .72 c

Table 3-4: Mean basal area growth (cm^2) for saplings within year, treatment type, and viability class. Letters correspond to significant differences within treatment type and year. Treatment means were significantly higher than control means within all year and viability class combinations. Differing Roman numerals indicate significant differences between 2009 and 2010 within treatment and viability class.

Within 2009, 2010, and both years and all four viability classes, treatment saplings put on significantly more basal area than control saplings. In 2009, treatment means in each viability class were roughly five times higher than controls. This jumped to 11+ times higher in 2010, as treatment saplings across all viability classes (except class 3) showed significantly more growth in that year than in the previous, while control saplings in all viability classes showed no change (Table 3-4).

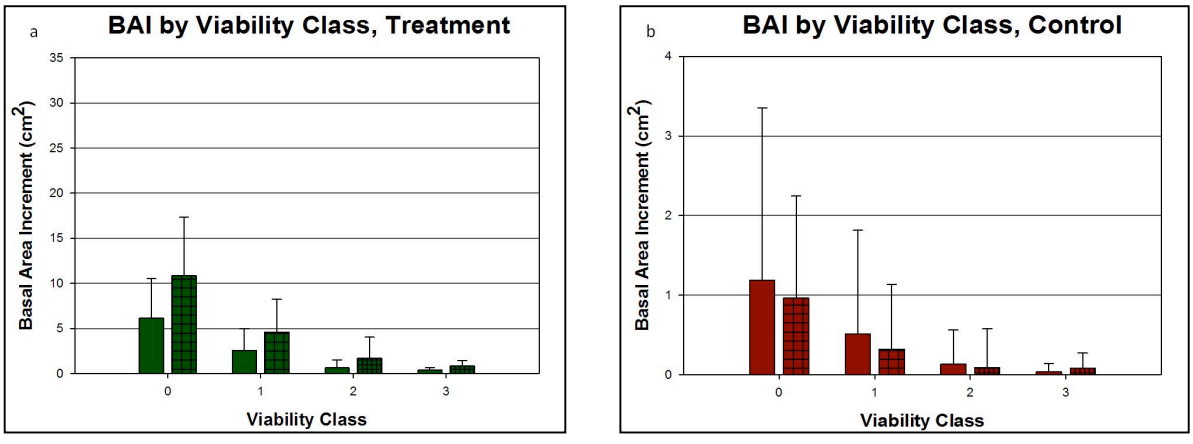

Fig.3-12: A visualization of values from Table 3-4 above. Green (a) represents treatment saplings and maroon (b) represents control. All error bars represent 1 standard deviation. Solid bars are 2009 values and checkered bars are 2010 values. Note the difference in scale between a and b.

Relative Growth

Relative basal area growth rates also show that control saplings grew far less than those released, both in 2009 and 2010 (Table 3-5). Treatment relative growth rates increased from 2009 to 2010 ($p = 0.0001$), while control growth rates remained stable (Table 3-5). Interestingly, relative growth rates showed a differing pattern from raw growth in that smaller saplings put on far more wood in relation to their initial size than initially larger saplings (Fig. 3-13). Both post-release years saw some treatment and control saplings put on well over 100% of their own initial size (Fig. 3-13), though far more treatment than control saplings were able to do this. Standard deviation of control saplings in both years was very high, especially in 2009 (Table 3-5). As a great deal of individuals added essentially no wood, and a minority added well over 100%, such high variability is to be expected.

RGR_{BA}	**Treatment**	**Control**
2009	18.1 +/- $21^{a, I}$	3.93 +/- $13^{b, I}$
2010	23.8 +/- $22^{a,II}$	4.04 +/- $7^{b, I}$

Table 3-5: Relative growth (% of previous year's basal area) from all treatment and all control saplings for 2009 and 2010. Differing letters indicate significantly different means between treatment within year. Differing Roman numerals indicate significantly different means between years within treatment.

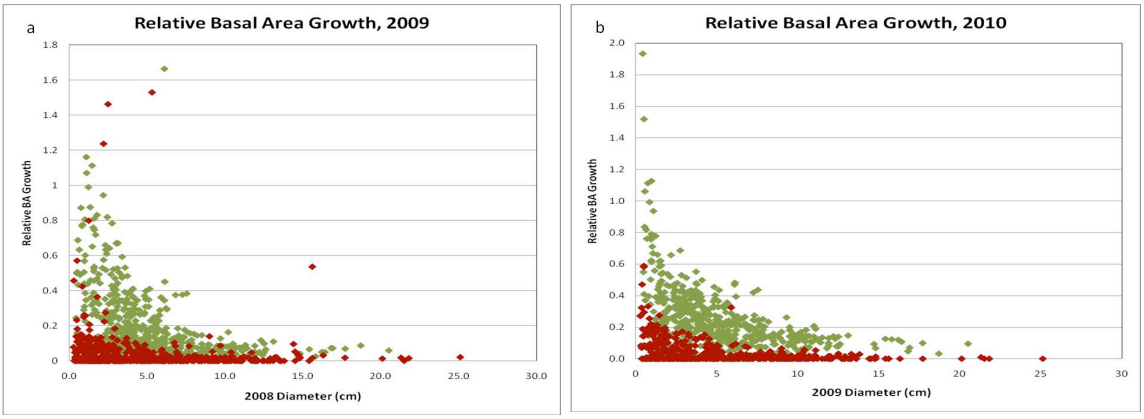

Fig.3-13: Relative basal area growth (fraction of previous year's basal area) of all treatment (green) and control (maroon) saplings vs. previous year's diameter from the 2009 (a) and 2010 (b) growing seasons.

Diameter Increment Growth

Despite issues with growth relative to initial size/age, diameter increment for saplings is reported in order to compare basic diameter growth values from this study with those from a wide range of others. Diameter increments from other studies cannot be converted to basal area increment unless the beginning and ending size of individual stems are reported, which is not the norm. In the first growing season, diameter increment growth of all saplings ranged from 0 cm to 1.7 cm, with an overall mean of 0.18 ± 0.23 cm. Treatment saplings grew an average of 0.29 ± 0.25 cm and control saplings grew 0.055 ± 0.14 cm (Table 3-6). Interestingly, larger saplings (>5 cm) showed significantly less absolute growth overall in control plots than small saplings, and in treatment plots were not significantly different (Table 3-6). This trend highlights the importance of examining basal area increment. Despite nearly the same control means in 2010 for both large and small groups, there was no significant difference between the two.

Diameter Increment in cm ± 1 S.D.	TREATMENT	CONTROL	OVERALL
All Saplings 2009	$0.29 \pm 0.25^{a,I}$	$0.055 \pm 0.14^{b,I}$	$0.179 \pm 0.23^{c,I}$
Plot Averages 2009	0.32 ± 0.16^{a}	0.071 ± 0.08^{b}	0.197 ± 0.18^{c}
All Saplings 2010	$0.48 \pm 0.29^{a,II}$	$0.056 \pm 0.09^{b,I}$	$0.288 \pm 0.31^{c,II}$
Plot Averages 2010	0.49 ± 0.12^{a}	0.056 ± 0.03^{b}	0.271 ± 0.13^{c}
All Saplings Both Years	0.78 ± 0.51^{a}	0.107 ± 0.21^{b}	0.471 ± 0.53^{c}
Plot Averages Both Years	0.84 ± 0.25^{a}	0.120 ± 0.10^{b}	0.451 ± 0.25^{c}

Table 3-6: Mean diameter increment growth for saplings within year, treatment type, and averaging method. Letters correspond to significant differences within treatment type and year. Differing Roman numerals denote significant differences between 2009 and 2010.

Diam. Increment in cm +/- 1 st. dev.		TREATMENT	CONTROL	OVERALL
1st Year (2009)	***< 5cm***	$0.29 \pm 0.24^{a,I}$	$0.06 \pm 0.15^{a,I}$	$0.19 +/- 0.24^{a,I}$
	>5cm	$0.29 \pm 0.25^{a,I}$	$0.05 \pm .08^{b,I}$	$0.17 +/- 0.22^{b,I}$
2nd Year (2010)	***< 5cm***	$0.44 \pm 0.27^{a,II}$	$0.06 \pm 0.07^{a,I}$	$0.28 +/-0.28^{a,II}$
	>5cm	$0.54 \pm 0.31^{a,II}$	$0.05 \pm 0.11^{a,I}$	$0.30 +/- 0.34^{a,II}$
Both Years (2008-2010)	***< 5cm***	0.74 ± 0.51^{a}	0.13 ± 0.25^{a}	$0.47 +/- 0.52^{a}$
	>5cm	0.83 ± 0.79^{a}	0.08 ± 0.13^{a}	$0.47 +/- 0.53^{a}$

Table 3-7: Mean diameter increment growth of saplings initially less than or greater than 5 cm diameter across 1st, 2nd, and both years of study and grouped by treatment or treatment and plot. Differing letters denote significant differences between size classes within year and treatment. Differing Roman numerals denote significant differences between 2009 and 2010 within treatment and size class.

In 2010, diameter growth of all control saplings was nearly the same as in 2009, at 0.056 ± .09 cm, while treatment saplings increased 66% to 0.48 ± 0.29 cm (Table 3-6). By this second post-release year, diameter growth of large and small saplings was statistically similar for all three treatment categories.

Natural Gap Sapling Growth

Saplings located in natural gaps displayed very large basal area increases, ranging from 5.3 to over 100 cm^2 over two years (0.35 – 3.7 cm diameter). Two of these

individuals grew over 1.4 cm in diameter both years of measurement, which is comparable to the very highest rates of growth of Broadneck adult canopy baldcypress. First year (2009) mean growth was 16.24 +/- 12.9 cm^2, and 2nd year (2010) mean growth

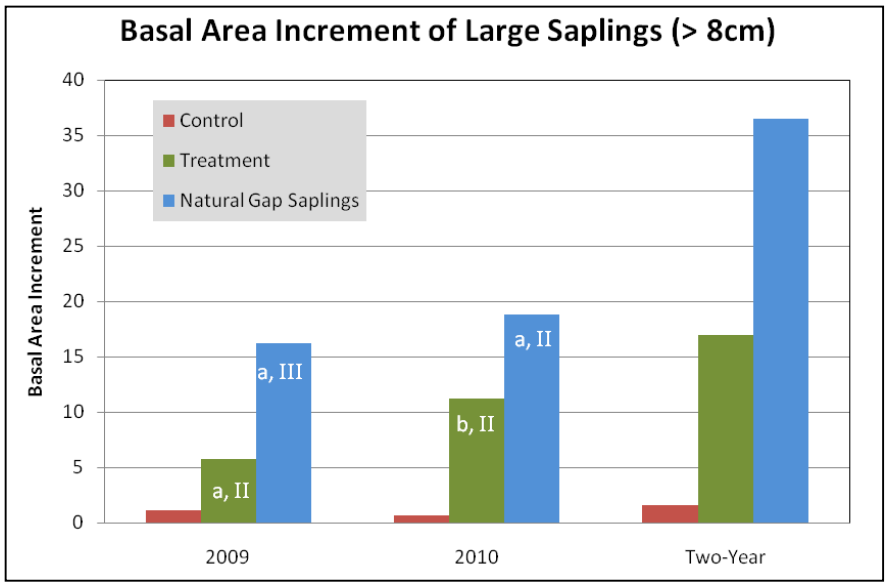

Fig. 3-14: Basal area increment of saplings > 8 cm growing in natural canopy gaps, control plots, and treatment plots. Differing letters indicate significant differences between years within treatment. Differing roman numerals indicate significant differences between treatments within year. Total two-year growth data was excluded from comparisons.

was 18.78 +/- 20.2 cm^2 – a slight difference which was not significant (p = 0.34). Saplings in natural gaps outgrew released saplings in the first year post-release, but by 2010 the difference was not significant (Fig. 3-14). Thus, it may not take long for released saplings to reach optimal but stable levels of high-light growth.

Mortality

Saplings within both control and treatment plots showed a relatively high mortality rate over the 2-year period. In the 1st year following canopy gap creation, overall treatment mortality rate was 11.8% and control was 9.0%, but the difference was not significant (p= 0.402, Table 3-8). First-year plot mean mortalities ranged from 0 to

nearly 30% (Appendix E). The majority of saplings who died in the first year were in the 0-3 cm size class in treatment plots and the 3-6 cm class in controls (Fig. 3-15).

Mortality (%) +/- 1 S.D.	Treatment	Control	Overall
1st Year (2008-2009)	11.8 +/- 9.9^{a,I}	9.0 +/- 7.6^{a,I}	10.0 +/- 8.7^{a,I}
2nd Year (2009-2010)	2.5 +/- 2.7^{a,II}	8.6 +/- 8.7^{b,I}	5.5 +/- 7.0^{b,II}
Both Years (2008-2010)	15.8 +/- 8.2^{a}	15.0 +/- 13.4^{a}	14.0 +/- 10.9^{a}

Table 3-8: Percent mortality in treatment, control, and overall saplings for 2008-2009, 2009-2010, and 2008-2010. Differences in letter indicate significant differences within year across treatment type. Changes in Roman numeral indicate significant differences within treatment between 1st and 2nd year of study.

In year two, treatment mortality ranged from 0 - 8.7% beneath gaps and from 0 - 23.3% beneath intact canopy. Notably, sapling mortality decreased significantly within treatment plots in the 2nd year following gap formation, to 2.5% (p= 0.011, Table 3-8). Control sapling mortality was nearly identical in year 2 to year 1 (Table 3-8). Thus, though treatment and control total mortality were nearly equal over the entire two years following gap creation, it appears saplings in treatment plots are dying less frequently over time, and this trend may lead to much higher long-term rates of survival within gaps.

Fig. 3-15 shows mortality rate across diameter classes for both treatment

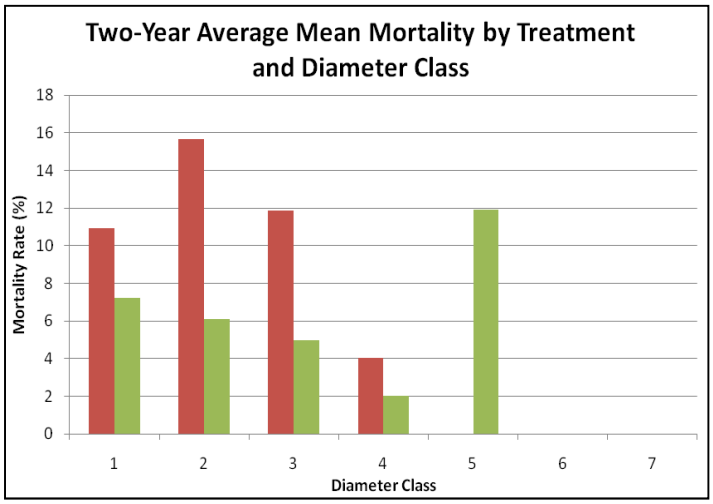

*Fig.3-15: Two-year mortality rates across initial diameter classes. Green represents treatment plot saplings and maroon represents control plot saplings. Diameter classes are as follows: **1** = 0 – 3 cm; **2** = 3.1 – 6 cm; **3** = 6.1 – 9 cm; **4** = 9.1 – 12 cm; **5** = 12.1 – 15 cm; **6** = 15.1 – 18 cm; **7** = >18 cm. Diameter classes 6 and 7 (and control saplings in class 5) showed no death over the 2-year period.*

types. No saplings in the largest classes (15.1-18 cm and >18 cm) in either treatment type died over the two-year study period. Treatment saplings showed decreasing mortality with increasing diameter over the four smallest diameter classes, but jumped to nearly 12% in the 12-15 cm class.

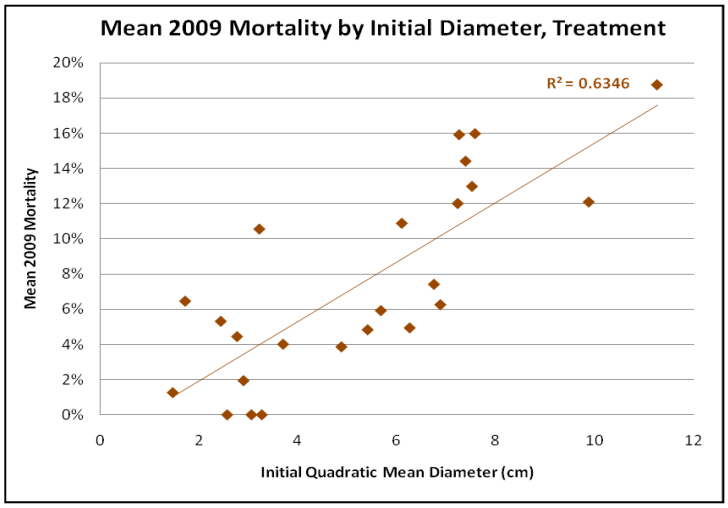

Fig.3-16: Regression of 2009 plot mean mortality rates by initial plot mean quadratic diameter. Control and treatment plots are lumped together.

Fewer control than treatment saplings died in the smallest size class, but far more died in the 3 – 9 cm size range (Fig. 3-15). A regression of plot mean mortality by initial plot diameter was highly significant ($R^2 = .63$, $p < 0.0001$; Fig.3-16), indicating a correlation between the average size of trees in a cluster and the cluster's rate of death.

Forest-Wide Survey

The Broadneck Swamp tract of the Roanoke River National Wildlife Refuge is approximately 405 ha in size. The sampling procedure for the survey provided a total sample size of 46,512 m^2 (102 plots at 456 m^2), or 4.65 ha – just over 1% of the total area. As noted in Chapter 2, 24 plots were situated within soil series other than Wehadkee Loam, the series hosting the vast majority of tupelo-dominated stands on the floodplain. All 24 plots occurred on Chewacla soil series, distinguished mainly by a slightly deeper water table (15 – 61 cm) and a slightly coarser texture within the upper profile. These soils occur as natural levees closer to the river, but also occur in areas of increasing elevation on the far side of the backswamp from the river. The northern boundary of the

survey was the Town Swamp Rd., which itself lies along a high ridge at the edge of the floodplain (Fig. 1-1).

The survey found a total of 26 species, some of which were only present on bottomland hardwood zone plots close to the river and on elevated ridges. These species are in green font below (Table 3-10). Unsurprisingly, water tupelo was the most dominant tree across the swamp, with an overall importance value of 44.37 (Table 3-9). Average water tupelo density and basal area were 348 trees/ha and 48.35 m^2/ha, respectively. This compares to overall density and basal area of 912.24 trees/ha and 68.45 m^2/ha, respectively. Water tupelo basal area was over six times the mean basal area of the next most abundant species – baldcypress – and, on average, water tupelo made up roughly 65% of total basal area across the floodplain. Quadratic mean diameter of all water tupelo across plots was 40.9 cm.

Canopy baldcypress (>25 cm dbh) occur at a frequency of 29.5/ha (about 7.8% of tupelo density and 3.2% of overall density) and at a basal area of 6.93 m^2/ha (about 13% of tupelo BA). Dq of all baldcypress was 39.73 cm. Dq of individuals >25 cm was 53.2 cm.

Importance Values also show that water tupelo strongly dominates (Table 3-9). Carolina ash is the next most important species, at 17.6, though its basal area is low and its Dq is small. Baldcypress, including saplings, has an importance value of 13.5 across the floodplain. 20 of the 26 species show importance values less than 3 when all plots are grouped together (Table 3-9).

Backswamp vs. Bottomland Hardwoods

Clearly, as with all wetlands, plant community composition and structure on the Roanoke River floodplain is largely driven by hydrology and associated soil characteristics. In order to better understand actual differences between lower, wetter backswamp areas and zones of higher elevation near the river, plot data was split by soil series and analyzed

separately. Plots lying outside the Wehadkee Loam soil series (backswamp) based on the USGS Soil Survey for Bertie County, NC (Fig. 2-3 brown lines) were grouped together as bottomland hardwood plots, and all others within this series were grouped as backswamp plots.

Species	IMP VALUE	Mean Basal Area (m^2/ha)	Mean Density (stems/ha)	Dq (cm)
***Nyssa aquatica* L.**	***44.37***	48.354	348.08	41.23
***Fraxinus caroliniana* Mill.**	***17.62***	1.494	288.31	8.12
***Taxodium distichum* L.**	***13.51***	7.588	117.39	39.73
***Acer rubrum* L.**	***6.65***	2.191	41.92	25.76
***Populus heterophylla* L.**	***3.16***	1.361	13.97	35.21
***Liquidambar styraciflua* L.**	***3.13***	1.319	15.48	32.94
***Fraxinus pennsylvanica* Marsh.**	***2.34***	1.514	10.96	41.93
***Ilex decidua* Walter**	***1.68***	0.062	21.07	6.11
***Quercus lyrata* Walter**	***1.37***	0.250	6.23	22.59
***Carpinus caroliniana* Walter**	***1.30***	0.124	11.82	8.59
***Quercus laurifolia* Mich.**	***1.15***	0.347	4.73	30.56
***Ulmus americana* L.**	***1.09***	0.309	3.65	32.82
***Platanus occidentalis* L.**	***0.81***	0.140	2.36	27.43
***Crataegus aestivalis* (Walter) Torr. & A. Gray**	***0.35***	0.033	1.29	18.09
***Celtis laevigata* Willd.**	***0.24***	0.108	1.07	35.84
***Diospyros virginiana* L.**	***0.19***	0.055	0.43	3.05
***Acer negundo* L.**	***0.19***	0.024	0.86	18.88
***Carya aquatica*(Mich. f.) Nutt.**	***0.17***	0.011	2.58	7.48
***Catalpa bignioides* Walter**	***0.12***	-	1.07	9.00
***Aesculus pavia* L.**	***0.11***	-	-	6.61
***Quercus michauxii* Nutt.**	***0.10***	0.011	-	14.92
***Quercus nigra* L.**	***0.09***	0.020	-	34.40
***Asimina triloba*(L.) Dunal**	***0.09***	-	-	3.77
***Betula nigra* L.**	***0.08***	-	-	20.60
***Carya glabra*(Mill.) Sweet**	***0.08***	-	-	7.80
***Itea virginica* L.**	***0.08***	-	-	1.80

Table 3-9: All woody species encountered in the forest-wide survey of the Broadneck swamp tract of the Roanoke River National Wildlife Refuge, along with their Importance value, mean basal area, mean density, and quadratic mean diameter. A "-" signifies <1 stem/ha or <.01 m^2/ha. The list was arranged by descending order of importance value.

Unfortunately, the soil survey was not precise enough to account for slight changes in elevation with isolated ridges that occur in areas of the backswamp which were visually noted to harbor plant communities more typical of bottomland hardwood zones. However, to selectively place plots on or near these ridges into the bottomland hardwoods group in a subjective manner would be biased, especially since many plots occur near the interface of the two soil series. In total, 24 plots – just under 25% of all plots – occurred on soil types other than Wehadkee and were grouped as bottomland hardwood plots.

Backswamp areas supported a far higher basal area than bottomland hardwood zones: 73.87 vs. 50.84 m^2/ha. However, backswamp areas support slightly fewer stems/ha (911 vs. 915 stems/ha). This means that average tree size must be larger in backswamps, which proves to be the case as overall backswamp and bottomland hardwood Dq were found to be 34.31 cm and 27.49 cm, respectively.

The most important species in bottomland hardwood zones (Table 3-10) were water tupelo, green ash, red maple, sweetgum, baldcypress, swamp cottonwood, Carolina ash, and laurel oak. In terms of stem density, water tupelo made up roughly 44% of backswamp plots but only 18.6% of bottomland hardwood plots.

Carolina ash was often the most abundant species in terms of number of stems, but this only tended to be the case in transition zones between backswamp and bottomland ridge with shallow standing water during floods. On higher ridges, the midstory was far less dense and usually populated by deciduous holly and ironwood. The overstory, especially in transition zones, was often heavily occupied by water tupelo (overall basal area for water tupelo in the bottomland hardwood zone was 24.86 m^2/ha – considerably less than its overall basal area of 53.03 m^2/ha). In terms of stem density, water tupelo made up over 54% of backswamp plots but only 18.6% of bottomland hardwood plots. The

overstory of higher ridges was usually occupied by some mixture of green ash, sweetgum, red maple, American elm, and overcup oak (*Quercus lyrata*).

Species	IMP VAL	Mean Den (stems/ha)	Mean BA (m^2/ha)
Nyssa aquatica	**25.71**	183.87	24.86
Fraxinus caroliniana	**13.06**	263.16	1.48
Acer rubrum	**11.23**	102.9	5
Fraxinus pennsylvanica	**7.44**	37.96	5.61
Liquidambar styraciflua	**6.85**	45.55	3.72
Taxodium distichum	**6.50**	59.04	3
Ilex decidua	**4.92**	75.91	0.23
Populus heterophylla	**4.82**	25.3	2.86
Carpinus carolniana Walt.	**3.70**	46.39	0.27
Quercus laurifolia	**3.10**	17.71	1.23
Quercus lyrata	**2.54**	15.18	0.51
Ulmus americana	**2.25**	10.12	0.9
Platanus occidentalis	**1.55**	6.75	0.3
Carya aquatica	**1.07**	8.43	0.04
Aesculus pavia L.	**0.87**	3.37	0.01
Celtis laevigata Willd.	**0.80**	4.22	0.43
Craetagus aestivalis	**0.78**	4.22	0.12
Quercus michauxii Nutt.	**0.67**	2.53	0.04
Acer negundo L.	**0.55**	3.37	0.09
Asimina triloba (L.) Dunal	**0.44**	1.69	-
Diospyros virginiana L.	**0.44**	1.69	-
Quercus nigra L.	**0.27**	-	0.08
Betula nigra	**0.23**	-	0.03
Carya glabra (Mill) Sweet	**0.22**	-	-

Table 3-10: Importance Value, mean density, and mean basal area of all species encountered in 24 plots located on Chewacla soil series. Species are organized by importance value, from most to least important. Species in green font were found only on this soil type. A "-" signifies <1 stem/ha or <0.01 m^2/ha. The list was arranged by descending order of importance value.

Snags taller than 3.05 m and with a measurable dbh were found to occur at a density of 16.3/ha. Though they appeared to be scattered somewhat evenly across the floodplain, no

very large old-growth baldcypress (>100 cm diameter) were captured in the survey of Broadneck Swamp.

Baldcypress Sapling Distribution and Abundance

Across the Broadneck swamp, baldcypress saplings were patchily distributed, usually occurring in clusters (much like those in canopy-gap experiment plots) along transition zones near the interface of Chewacla and Wehadkee soil series – where flooding is frequent but generally shallower than in the deep backswamp (Fig. 2-2). Though highly clustered spatially, baldcypress saplings occurred at a frequency of just over 4 per plot, or 80.8/ha. In plots with over 10 saplings, sapling basal area averaged 5.42 m^2/ha – similar to overall canopy baldcypress basal area.

Of the 12 plots with 5 or more baldcypress saplings (the overall mean/plot was 4.01), 9 were centered on Wehadkee (backswamp) soils, but 7 were within 120 m of the official boundary between soil types. These included 6 of the 9 plots with more than 10 saplings (and all 3 supporting over 50 saplings). Of the 33 plots with two or more adult baldcypress (overall mean was 1.34/plot), all but three were located on the backswamp soil type, and only 12 of the 33 were within 120 m of the soil boundary. Thus, it appears wetter growing-season conditions in the post-dam era may have caused a shift in spatial regeneration patterns, though in theory one or only a handful of relatively dry growing seasons could have led to adult baldcypress' wider distribution.

Saplings all the way to 25 cm dbh were found in sample plots, but those greater than 13 cm were quite rare (Fig.3-17), making up only 7.67% of the total. Saplings 1-5 cm comprised nearly 54% of all those found, and saplings 5-9 cm comprised a further 27.4%. Most of these saplings are in a similar condition to understory saplings utilized in the canopy gap study – stressed with lots of epicormic branching, relatively sparse

foliage, and sometimes chlorotic leaves and dieback. Superficially, larger saplings usually appear more stressed than smaller saplings.

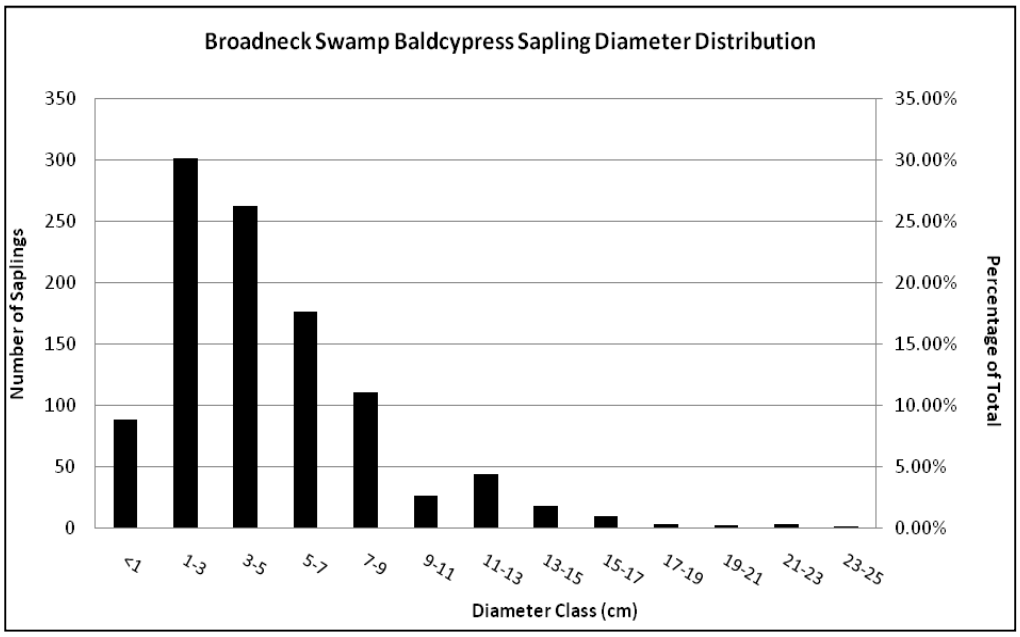

Fig.3-17: Diameter distribution of baldcypress saplings sampled in survey plots across the Broadneck swamp

CHAPTER 4 – DISCUSSION

Sapling Ages

The range in sapling ages ranged over was greater than expected, and it appears that at least four cohorts exist on the floodplain. Conner and Muller (1989) found that sub-canopy baldcypress saplings near Lake Pontchartrain, LA averaged 8.9 cm in dbh (similar to many of the plots in this study) and were mostly 32-35 years old, with a few (12 of 50) being slightly younger. This is comparable with Broadneck saplings, which, at roughly 8 cm dbh varied between 15-30 years old (Fig. 3-2). The Broadneck Swamp sapling age-diameter relationship was positive and significant, but the R^2 value was relatively low (.26). The observed amount of variability in age at a given diameter might be expected for suppressed saplings growing at such low rates (and 42% not growing at all). This is also supported by the fact that larger (>5 cm) and smaller (< 5 cm) saplings share similar rates of zero growth. A study of codominant oak growth in northeast Kansas found significant age-diameter relationships with R^2 values of .33 - .96 (Abrams 1985), and a study of northern hardwoods in virgin stands found age and diameter fairly well correlated with R^2's of .47 - .92 (Leak 1985). Thus, though a weak positive relationship exists, larger Broadneck saplings are not necessarily older than smaller ones.

Light Conditions Pre- and Post-Treatment

Light levels beneath both full overstory canopy and the variably dense baldcypress sapling layer in this study initially (2008) averaged 1.27% full sun. We do not know light levels available to the saplings at the midstory level, but it is likely they are higher than 1.27%. This may be compared to a study by Lin et al. (2004), who found light levels just above randomly selected saplings in a floodplain forest ranged from 0.1 – 25.5% full sun, with an overall average of 4.5%. Ice storm disturbance in a northern

hardwood forest produced similar understory DIFN's of 0.1 - 0.23 (Rhoads et al. 2004). Parker et al. (2008) found DIFN beneath small (38 m^2) gaps in a red pine plantation produced DIFN of 28.7 and LAI of 1.71 – toward the higher end of values from this study. This was compared to a control DIFN of 6.7. Light levels in the larger gaps of this study would probably have equaled or exceeded those of Parker et al. if the influence of midstory saplings did not exist. Regardless, it is clear from changes in DIFN that death of overstory trees in a 456 m^2 area produced significant changes in understory light conditions to a degree adequate to influence sapling growth.

Growth

Strong differences between treatment and control sapling growth and mortality indicate that *Habitat* did not have a negative effect on baldcypress saplings. Mortality in treatment plots was high initially, but mortality in control plots was equally high and stayed that way into 2010, while death in treatment plots dropped considerably. Recently, Gresham (2010) found no effects of *Habitat* 'hack-n-squirt' treatment of Chinese tallow (*Triadica sebifera* [L.] Small) on nearby live oaks (*Quercus virginiana* Mill.). Though the herbicide does remain active in the soil for an extended period (BASF 2004), it may not leak as readily from roots as feared.

Basal area increment values of released baldcypress saplings ranged between 0 and 23 cm^2 in the 1st post-release growing season (mean: 2.38 cm^2) and between 0 and 32 cm^2 in the 2nd (mean: 4.53 cm^2). Though these means are generally well below that of adult baldcypress from backswamps of both Broadneck Swamp (range: 5 – 70-80 cm^2; long-term mean: 24.27 cm^2; Doyle and deGravelles 2010, Unpublished Data) and the Congaree River, SC (range: 7 – 52 cm^2; Palta et al. 2010), the largest 19 (or top 25%) released sapling averages were significantly higher (1st year mean: 6.26 cm^2; 2nd year mean: 10.18 cm^2). Also, growth between year 1 and 2 increased significantly among all

treatment saplings with a difference of 2.15 cm^2. Growth of the largest saplings in each plot increased 3.92 cm^2 from year 1 to year 2. A continued rate of such an increase in growth would quickly bring these largest saplings near the long-term mean of adult baldcypress of Broadneck Swamp. As a comparison, McClurkin (1965) found young baldcypress of a mean dbh slightly larger than those in this study and in pure stands thinned from 23.9 m^2/ha to 18.5 m^2/ha grew 11.1 cm^2/yr over 3 years following thinning, while those in an un-thinned stand grew at 9.03 cm^2/yr. This growth is comparable with the largest saplings in treatment plots of this study. Conner and Day (1992) found BAIs of adults from a variety of sites in South Louisiana (range: 14 – 50 cm^2; means of four hydrologically different sites range from 17.4 cm^2 – 24.5 cm^2) similar to those of adults from Broadneck Swamp. Codominant baldcypress at freshwater coastal sites in SC and LA similarly averaged 15 – 23 cm^2 annual basal area growth over three years (Krauss et al. 2009), but baldcypress > 5cm dbh at a subsiding site in the upper Barataria Basin, LA increased only 7 ± 1.5 cm^2/year over five years (Visser and Sasser 1995).

In contrast, saplings beneath unbroken canopy grew far less and without change from 2009 to 2010 (1st year mean: 0.055 cm^2; 2nd year mean: 0.056 cm^2). The largest saplings in these sites put on more growth than the all-saplings group (1st year mean: 1.0 cm^2; 2nd year mean: 0.73 cm^2), but still far less than their treatment counterparts and even less than treatment saplings initially 5 cm and less in diameter. Thus, it is clear that baldcypress saplings within this age range are able to utilize increased light and soil resources from canopy gaps of moderate size for immediate improvement in diameter growth and productivity following years of low-light growth.

Of course, a two-year study provides a very limited view of growth response, which may or may not continue to improve. A study of grand fir saplings released in northern Idaho found a plateau in growth following an initial boost from pre-release levels (Ferguson and Adams 1980), and a study of various species in California found no

significant growth response until an average of 2-4 years following release (Helms and Standiford 1985). Very strong growth of Broadneck Swamp saplings found in natural gaps may suggest that observed growth rates will continue for many years, but it is impossible to know if these saplings have grown beneath gaps since seedling stage or whether they were subjected to suppression similar to plot saplings.

Baldcypress diameter increment values have been reported far more often than BAI in the literature. Though it is unfair to compare diameter growth of small trees with that of much larger ones, it nonetheless provides an indication of how quickly trees are progressing toward an "adult" size class (25+ cm dbh in this case). Conner and Inabinnette (2003) note that most studies have found baldcypress diameter growth in the range of 0.3 - 0.54 cm/yr, though much variability exists and trees in impounded wetlands often put on less growth than this. Table 3-11 shows diameter increments from this study alongside those of a variety of past studies. Within two years following release, Broadneck Swamp saplings displayed diameter growth rates within the above range and comparable to those of similar and larger size classes from a range of other Southeastern sites and hydrologic regimes.

In terms of basal area growth, however, canopy baldcypress from some of these other studies (*i.e.* Mattoon 1915, Sternitske 1955, Mitsch et al. 1979) added far more wood than released Broadneck saplings. Other studies show that baldcypress is capable of responding to various levels of thinning with very strong diameter growth, whether in mostly pure (Williston 1969, Prenger 1985) or mixed (McGarity 1979) stands.

Prenger (1985) found diameter growth of unreleased suppressed adult (63 years old) baldcypress to average 0.035 cm across a five-year period - levels similar to unreleased saplings in this study. Released saplings from Broadneck Swamp outperformed (in terms of diameter increment) Prenger's (1985) initially suppressed trees

which survived a heavy thinning to 23 m^2/ha, or 45% of the initial basal area (0.39 vs. 0.22 cm; Table 3-10).

Study	Location	Diam. Inc. (cm/yr)	Type of Stand
This Study	North Carolina	0.39	Released sub-canopy baldcypress
This Study	North Carolina	0.05	Unreleased sub-canopy baldcypress
This Study	North Carolina	0.41	Canopy dominants (long-term mean)
Mattoon 1915	Maryland	0.54	2nd growth baldcypress
Mattoon 1915	Louisiana	(0.25 - 0.29)	Virgin baldcypress
Sternitske 1955	Louisiana	0.46	15 – 30 cm baldcypress
Sternitske 1955	Louisiana	0.53	36 – 46 cm baldcypress
Sternitzke 1955	Louisiana	0.51	51 – 71 cm baldcypress
Williston 1969	Mississippi	0.45	75-80 yr old baldcypress thinned to 34-46 m^2
Mitsch et al. 1979	Illinois	0.2 - 0.59	Baldcypress permanently flooded
Day 1985	Virginia	0.12	Baldcypress flooded Jan. – June
Keeland & Sharitz 1995	South Carolina	0.1 - 0.4	Backswamp canopy baldcypress/tupelo
Keeland & Sharitz 1995	South Carolina	0.1 - 0.33	Backswamp sub-canopy baldcypress/tupelo
Keeland et al. 1997	SC & LA	0.30	Baldcypress/tupelo during wet years
McGarity 1979	Florida	0.15	Mixed cypress/hardwood no thinning (37 m^2/ha)
McGarity 1979	Florida	0.38	Mixed cypress/hardwood thinned to 23 m^2/ha
McGarity 1979	Florida	0.4	Mixed cypress/hardwood thinned to 16 m^2/ha
McGarity 1979	Florida	0.6	Mixed cypress/hardwood thinned to 9 m^2/ha
Prenger 1985	Louisiana	0.035	Suppressed control baldcypress
Prenger 1985	Louisiana	0.25	Dominant canopy control baldcypress
Prenger 1985	Louisiana	0.22	Suppressed baldcypress thinned to 23 m^2/ha
Prenger 1985	Louisiana	0.51	Dominant baldcypress thinned to 23 m^2/ha
Dicke & Toliver 1990	Louisiana	0.16	Periodically flooded 2nd growth baldcypress
Dicke & Toliver 1990	Louisiana	0.16	Continuously flooded 2nd growth baldcypress

Table 3-11: Baldcypress diameter increment growth rates from various past studies. Growth rates represent per year diameter increments, but some were calculated as the average of longer-term cumulative growth. Growth values from this study represent per year means of the two-year total growth. Ranges in parentheses are total growth ranges. Those not in parentheses are means of various sites or periods.

Despite the age of the stand in that study, and probable length of suppression of those trees in the sub-canopy, heavy thinning clearly led to positive effects on growth. Over all classes, baldcypress diameter increased 1.96 cm over 5 years, or 0.39 cm/yr – the same amount as saplings released in this study, though, as noted previously, direct diameter growth comparisons between trees of differing initial diameters are not fair.

Baldcypress' ability to respond immediately to increases in light from release is similar to shade tolerant species in other ecosystems. Wright et al. (2000) found that long (and often multiple) periods of suppression did not affect the ability of various shade tolerant boreal tree species to respond to release, while less tolerant species showed a lag

in response time, but eventually also responded with increased growth. This characteristic, along with the near zero growth of unreleased saplings, might suggest baldcypress exists closer to the end of Canham's (1989) shade tolerance gradient in which a species is able to survive continuously without much growth but respond well to an overhead gap. However, smaller saplings' stronger relative growth in deep shade, coupled with high sub-canopy mortality rates observed, push baldcypress in the gradient's other direction.

Yoshida and Kamitani (1998) found RGR_{BA}'s of four deciduous hardwood species to be between 2 and 4%/yr for most individuals 21 – 29 cm (mostly larger than saplings in this study) over a four year period following release along the edge of variously-sized canopy gaps. RGR_{BA}'s of released saplings from this study were considerably higher – with a mean of roughly 18% in 2009 and 24% in 2010. Unreleased saplings averaged roughly 4% per year – closer to Yoshida and Kamitani (1998)'s released-tree means. Clearly, sub-canopy baldcypress – especially smaller individuals – are ready to utilize new light resources immediately. Karlsson et al. (2006) report similar mean RGR_{BA} of 4.6% (+/- 3.4% S.D.) of Norway spruce (*Picea abies* L. Karst.) subjected to slowly increasing amounts of ground-level ozone in Sweden. Stand basal area was the strongest predictor of RGR_{BA}, and younger stands (19 years vs. 26 – 32) showed RGR_{BA} values closer to those of this study (14 – 18%).

It should be re-iterated that RGR_{BA} as calculated in this report is technically a mean relative growth rate, which inherently ignores the fact that the percentage of growth in relation to diameter naturally changes as tree size changes (South 1995). However, neither of the compared studies - Yoshida and Kamitani (1998) nor Karlsson et al. (2006) - calculated a mean relative production rate.

Effects of Initial Size

There was a positive relationship between initial sapling size and basal area growth response to release in both post-treatment years, but no relationship existed among unreleased saplings (Fig. 3-9 a and b). For trees across all size classes in free-to-grow, even-aged stands, growth should be expected to increase with initial diameter because there is generally a strong relationship between diameter and crown and leaf area in these stands (Dean and Long 1986). In terms of basal area increment, treatment varied positively and significantly across initial diameter (Fig. 3-8a). Larger trees did not outperform smaller trees in terms of diameter increment (Table 3-8), and treatment plots outperformed control plots by a decreasing margin as quadratic mean diameter increased (Fig. 3-8b). This is interesting as it means that smaller saplings could eventually "catch up" to larger neighbors in size over time, but as BAI inherently takes into account total wood production, it is the better metric of growth response. Hokka and Groot (1999) found steady increases in BAI of roughly 0 cm^2/yr to 6 cm^2/yr across a range of 0 – 25 cm initial diameter for older stands. Younger stands showed a much sharper increase in growth across a smaller range in diameter. West (1980) similarly showed BAI increased in even-aged 56-year old Tasmanian *Eucalyptus* from 0 cm^2/yr at 20 cm dbh (and smaller) to 40 – 60 cm^2/yr for stems larger than 50 cm dbh.

There have been few studies which examined baldcypress growth across initial size classes. Dicke and Toliver (1990) observed that there was a similar positive relationship between initial size and growth over 5 years for nearly pure second-growth baldcypress stands in the Atchafalaya Basin, LA subjected to either seasonal or continuous flooding. In that study, continuously flooded trees in the 45-cm class outgrew trees in the 10-cm class by over 4 times (Dicke and Toliver 1990). Trees so widely different in initial size were clearly receiving various amounts of radiation despite being

of an even-aged stand just 63 years old. Such appears to be the difference between growth across a size gradient for even-aged baldcypress and those of this study – all in a sub-canopy position - which did not vary in growth across classes. This suggests that radiation beneath normal swamp canopies is too low to provide what is otherwise an advantage to being initially large, and all size classes are growing minimally in diameter as they struggle to acquire enough resources to survive. It is important to recognize, however, that sub-canopy saplings visually recognized as healthier (top 2 viability classes) put on significantly more growth than weaker/dying trees. However, this viability class system made no distinction between healthy large trees and healthy small trees.

The only study examining post-release growth across a range of initial baldcypress diameters was Dicke and Toliver (1988)'s study of response to thinning to various residual basal areas in another baldcypress-dominated stand in the Atchafalaya Basin, LA. They found that initial tree diameter was the most important factor influencing 5-year diameter growth in response to thinning (Fig. 3-18), explaining 30% of the variation in growth. Average growth of larger trees (35.6 cm) in that even-aged, second-growth stand was 9 times that of the smallest trees

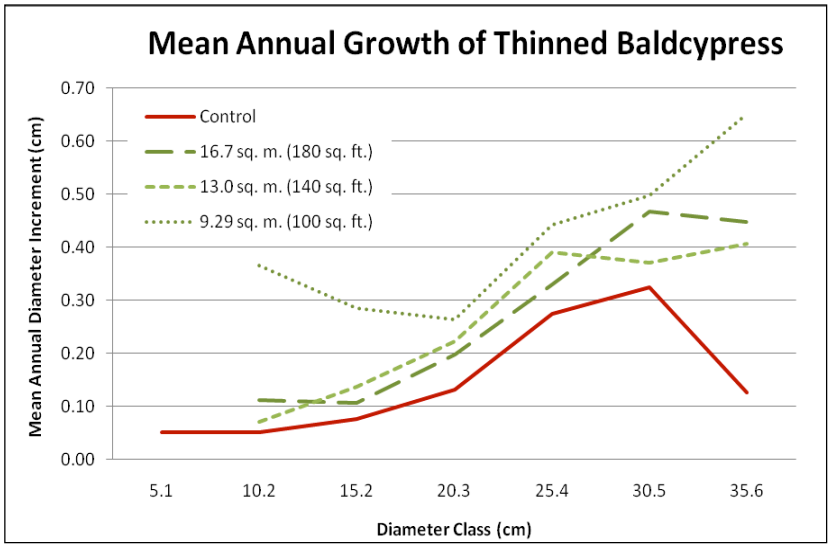

Fig. 3-18: Mean annual baldcypress diameter increment over five years following thinning to various residual basal areas in the Atchafalaya Basin, LA. The figure was produced with data obtained from Dicke and Toliver (1988).

(5.1 cm). Despite this, the authors suggest that long-term development in high density conditions kept larger baldcypress from responding with growth equivalent to that of similar-sized trees from a 31-year-old plantation in Mississippi with comparable basal area (see Krinard and Johnson 1987).

However, baldcypress growth varies quite widely site to site, and Dicke and Toliver's control mean of 0.16 cm/yr is lower than growth at many other sites from the literature (Table 3-11). Also, it should be noted that Krinard and Johnson (1987)'s recorded mean annual growth of 35.6 cm trees was 1.78 cm – a rate far higher than means from other published studies (Table 3-11). These studies highlight the wide differences in growth potential among baldcypress at various sites.

The correlation between size and growth response within plots was stronger for treatment saplings than control across almost all mean cluster sizes (Fig. 3-11). Thus, larger released trees seem able to immediately begin taking advantage of greater crown space and soil resource access. Among unreleased saplings, the correlation between size and growth response appears stronger for clusters with a smaller mean size (Fig.3-11), hinting at the loss of size advantage as saplings become larger and with a more marginal net carbon balance.

This idea is strengthened by relative basal area growth results, which show smaller saplings in both released and unreleased conditions to be more growth efficient than larger saplings (Fig. 3-13). Clusters of smaller Dq also show lower mortality rates (Fig. 3-16), despite clusters with a larger Dq putting on more raw growth. A general consensus is that smaller trees are generally the victims of natural thinning (Westoby 1984). However, this is not necessarily always the case (Guan et al. 2008). Guan et al. (2008) note that when canopy closure sets in, larger individuals have more resources available but must maintain more non-productive tissues, and it is likely that the more intense competition becomes, smaller trees must become more growth efficient. This is

likely true for sub-canopy competitors, and may explain smaller trees' greater growth relative to unreleased counterparts.

A decline in growth efficiency could be due to a change in the net carbon balance as saplings become larger. Irrespective of age, sapling light requirements should increase with height due to increasing maintenance costs (Waring 1987, Givinish 1988), and, thus, small saplings should have greater carbon availability in the shade than larger saplings (Williams et al. 1999). Though they provided no tests of significance, Yoshida and Kamitani (1998) showed what appears to be a strong negative relationship between individual tree basal area (initial size) and relative growth rates for four different deciduous hardwood species, regardless of stand density.

Mortality

An initial concern was the rate of death of saplings, which appeared initially weak and stunted with abundant epicormic branching. At this point, sub-canopy saplings are dying at a rate far higher than that of adults in mature baldcypress-tupelo forests (Conner et al. 2002), which is not surprising. However, such high rates of mortality – roughly 8% - could not have been sustained over the lifespan of these saplings, suggesting that they have increased steadily with time or recently spiked in response to an environmental cue. Krinard and Johnson (1987) found mortality of planted baldcypress from age 21 to 31 averaged 4.3% per year, but only trees less than 18 cm died, and the highest mortality occurred in the 7.6 – 10.2 cm range. The mean diameter by age 31 was 21.8 cm.

Canopy gap creation did not affect Broadneck sapling mortality in the first post-release year, as treatment and control plots showed similarly high rates of mortality, but by year two canopy gap mortality rates had decreased significantly to levels near those of adults in normal, mature swamps. Fig. 3-16 shows that as average size within a cluster increases, more saplings die, which is probably both due to a decreasing net carbon

balance and more intense intra-sapling competition as sub-canopy space becomes more scarce. This is corroborated by the steep decline in abundance of baldcypress saplings larger than 7 cm across the floodplain (Fig. 3-17). Thus, it appears that baldcypress is more likely to die as the effects of suppression become more difficult to deal with over time. This likely has less to do with the age of the sapling than its carbon balance. Several studies have noted that there is a decline in the ratio of photosynthetic to non-photosynthetic tissues as the tree becomes larger and requires more resources to sustain itself (Canham 1989, Gerrish 1990).

A sapling's carbon balance, though affected by multiple environmental factors, is often light limited and directly related to mortality, as has been shown for numerous eastern hardwood and coniferous species (see Kobe et al. 1995). A marginal net carbon balance, coupled with stresses from periodic episodes of prolonged flooding or drought, may be a major driver of sapling mortality. Smaller saplings, with higher rates of relative growth (Fig. 3-13), are clearly further from such a marginal carbon balance and less likely to be killed by flood and/or drought stress. Guan et al. (2008) found that a larger size did not improve survivorship within even-aged Taiwanese Japanese cedar (*Cryptomeria japonica* [L.F.] D. Don) plantations over 50 years. They similarly suggested that mortality was more related to growth efficiency (relative growth) than initial size. However, Fig. 3-15 suggests that, within clusters, relative size is less important to survival year to year. This seems generally contradictory to the reasoning above, as smaller saplings would be expected to die, on average, less than larger saplings. It should be noted that no unreleased saplings in the largest three diameter classes died during the two-year study, though these were relatively rare to begin with.

Lin et al. (2004) showed that growth is a predictor of mortality in some floodplain species. In that study, baldcypress saplings were found to have among the lowest rates of mortality (mean of 2.9%) at zero growth over a 20-yr period (though significantly lower

than only 2 of the other 7 species), which would imply relatively strong shade tolerance. Saplings from that study were relatively small, however (<= 4 cm). Short-term results from this study, showing sub-canopy sapling mortality of more than 8%/yr across all size classes, contradict this. Many studies of various species have presented evidence in favor of a general negative correlation between high light growth and low light survival and similarly between high light growth and low light growth (Kobe et al. 1995, Lin et al. 2004, Gravel et al. 2010). The fact that baldcypress shows moderate height and diameter growth in high light relative to other floodplain species and is able to survive well in low light for an extended period (but apparently with limits) suggests that it is somewhere in the middle of such a gradient, and its past subjective label of "intermediate" shade tolerance holds true.

Treatment saplings dying at a rate of 11% in 2009 dropped to a 2.5% rate in 2010 in light levels ranging from roughly 6 – 25% of full sun. Light levels at sapling height were probably higher. This is in line with findings of Lin et al. (2004), who demonstrated that mortality of several floodplain species (water oak, sweetgum, and red maple) dropped to almost 0 at light levels above 10%.

Though flooding clearly has different effects on the mortality of different floodplain species, shade tolerant species seem to be at higher risk because their mortality seems to increase during flooding (Lin et al. 2004). However, species able to allocate carbon to growth rather than storage will in theory have a higher likelihood of survival because bigger individuals are less susceptible to flooding mortality than smaller individuals (Hall 1993). In the case of long-suppressed baldcypress, however, the opposite appears to hold true. In general, there seems to be a tradeoff between the effects of having to sustain a more marginal net carbon balance at larger sizes in a low-light sub-canopy environment and the benefit of being large relative to neighboring saplings in the competition for scarce resources.

Epicormic Branching

An "epicormic branch" is a "shoot arising from an adventitious or dormant bud on a stem or branch of a woody plant" (Harlow et al. 1996). This study did not measure any indicators of epicormic branching because future harvest of baldcypress for lumber production is not a short or long-term objective for Broadneck Swamp managers. However, it is an important aspect to consider when releasing species which readily sprout, such as baldcypress, if sawtimber is to be produced, because knotting from epicormic branches lowers the value of the wood. Epicormic branching is a common response of forest trees suddenly released to increased radiation along the bole, but sunlight is only a trigger mechanism, while genetics and tree health and stress prior to release largely dictate the amount of epicormic branching that will occur (Lockhart et al. 2006). A highly susceptible species of low vigor and poor health will often have epicormic branches even without sunlight (Lockhart et al. 2006), as is the case with Broadneck Swamp saplings. Dicke and Toliver (1988) found that removing 53% of a baldcypress stand's basal area (thinned to 9.29 m^2 [100 $ft.^2$]) produced moderate to heavy epicormic branching on the butt log of 27.5% of baldcypress trees. Consequently, the authors recommended reducing BA to 13.01 m^2 (140 $ft.^2$) – a 34% reduction in density – to optimize benefits gained from increased growth and the increased number epicormic branches that occur as residual basal area is lowered.

Broadneck saplings, which are putting on very little to no wood and are dying at high rates after many years of sub-canopy suppression, produced a great deal of epicormic branches even before being released. Though crowns of released saplings appear expanded and healthy (Fig. 3-5b), epicormic branching may increase, especially in plots with lower sapling density. Future studies of baldcypress sapling release would do

well to monitor this important factor, and managers should certainly consider its impact on future log values.

Forest-wide Survey

Floodplain forest composition is a function of the flood tolerance of individual tree species and how they respond to canopy gap light and shade (Battaglia and Sharitz 2006). Density and basal area of the Broadneck backswamp are at levels comparable to those of mature, undisturbed swamps with at least 50% baldcypress/water tupelo basal area from a variety of other studies (see Conner et al. 1981, Dicke and Toliver 1990, Smith 1996, Conner and Inabinnette 2003, Krauss et al. 2009) - that is, canopy tree densities of 800-1000/ha and basal areas of 50-80 m^2/ha.

The number of species found in this study (26) is nearly equal to the 25 reported by Smith (1996) from his comprehensive survey of the forest communities and the related geomorphic, hydrologic, and edaphic variables of the Cache River floodplain in northeastern Arkansas. Sixteen species are shared between the sites. At Broadneck Swamp, the Chewacla soil series supported only four more total species than the Wehadkee soil series, which was likely due to overlap in local species occurrence across an artificial soil boundary which does not adequately represent gradients in true edaphic characteristics. Water tupelo remained the most important species on the drier Chewacla series, but red maple, sweetgum, deciduous holly, swamp cottonwood, laurel oak, and overcup oak were all more abundant and thus caused a more even distribution of importance values. Carolina ash occurred only in plots at least 200 m from the river, and of the 10 plots (top 10%) with the highest Carolina ash abundances, 8 were located within 90 m of the official boundary line between soil series.

Baldcypress saplings were relatively patchy across the floodplain. At 80.8/ha, far too few exist to make significant changes in overstory composition via release, even if all

were to survive and replace canopy trees in existence. As noted above, thousands of seeds germinate across the floodplain during rare periods of drawdown during spring and summer, but the vast majority die from overtopping during extended flooding in fall, winter, and the following spring. Saplings in the 1-5 cm size range were by far the most abundant across Broadneck Swamp (~55% of the total; Fig. 3-17). These saplings initially responded well to canopy gap creation, showing increases of 4.08 cm^2 over two years, though this was significantly less than the 11.61 cm^2 put on by saplings greater than 5 cm in the same period.

In his survey, Smith (1996) found that water tupelo/baldcypress communities had greater depth of flooding by 0.7 – 1.5 m and greater duration of flooding by 94 – 120 days than nearby communities of slightly higher elevation. This led to greater soil organic matter (4.2% vs. 2.9-3.3%) and a lower cation exchange capacity (12 vs. 14-15.7 meq/100g). Similar to Broadneck Swamp, tree density (stems >/= 6.6 cm) for water tupelo/baldcypress was far higher than other forest types in that study (772 vs. 359 – 661 stems/ha), as was basal area (54 vs. 21 – 29.4 m^2/ha). The Broadneck backswamp was denser (911 stems/ha) and higher in basal area (73 m^2/ha) than the Cache River floodplain. Though Smith (1996) used a much narrower definition of saplings (2.5 – 6.6 cm), water tupelo/baldcypress communities showed relatively high shrub and sapling density, at 1236 stems/ha overall. Red maple (235/ha), sweetgum (79/ha), American elm (116/ha), water hickory (63/ha), and overcup oak (42/ha) were all more abundant as saplings than water tupelo (18/ha) and baldcypress (0/ha). By comparison, baldcypress saplings 2.5 - 6.6 cm in this study occurred in backswamp areas at 52.9/ha, and water tupelo of similar size were completely absent. In bottomland hardwood zones, baldcypress saplings of this size occurred at a density of 16.4/ha and water tupelo at a density of just 8.2/ha.

Thus, an important question remains as to why Broadneck Swamp has been able to produce multiple dense, if patchy, cohorts of baldcypress advanced regeneration despite a highly regulated and unnatural hydrologic regime. Smith's (1996) survey along the Cache River found a greater canopy baldcypress component in the backswamp (~21% of basal area vs. 11% for Broadneck), and yet found no baldcypress saplings (2.5 – 6.6 cm) at any elevation. However, another study documented baldcypress sub-canopy saplings (10-20 cm) at 50/ha in an undisturbed mature water tupelo-dominated forest (baldcypress canopy density ~16% of total) in South Carolina (DeSteven and Sharitz 1997). Past mass recruitment events had likely led to the establishment of these sub-canopy saplings, as no stems between 5 – 10 cm were found, and smaller saplings/seedlings were abundant. Conner and Flynn (1989) found 980 baldcypress seedlings/saplings (<10 cm)/ha on a flooded site in Louisiana, but this declined to 30/ha the following year and then, in relatively dry 1987, jumped to 1600/ha. This large fluctuation was due primarily to seedling recruitment during years with drawdowns during spring and summer and subsequent high flooding, causing death of most of the cohort.

Hydrology (namely hydroperiod) is the most important driver of woody vegetation composition on the lower Roanoke River floodplain (Townsend 2001), and it clearly plays a dominant role in patterns of baldcypress establishment. However, a secondary impediment may be occurring in the form of competition with Carolina ash, which, as noted previously, has been found to occupy similar transition zones. Though highly clustered, baldcypress saplings averaged just over 4 stems/plot across the study site. Carolina ash, which also tended to be clustered but far less so, averaged 13.15 stems/plot. Of the 28 plots which supported greater than the mean number of Carolina ash, only 4 also supported greater than the mean number of baldcypress. Only 15 supported baldcypress saplings at all. In general, Carolina ash is more well-distributed

across the study site, and every plot in which baldcypress occurs supports at least 1 Carolina ash stem, with Carolina ash usually more abundant.

It is unclear why Carolina ash might have an advantage over baldcypress, but given the general lack of baldcypress sapling overlap in areas of somewhat dense ash midstory, it is likely the former species is outcompeting the latter at early life history stages. Once established with crowns above floodwaters, both species are among the most flood tolerant trees in the Southeast (Ernst and Brooks 2003). Carolina ash may produce more or more well-distributed seed than baldcypress, but more likely its advantage is its ability to germinate in standing water and, once germinated, survive when overtopped by floodwaters (Hook 1984). Once established, low light conditions produced by a dense Carolina ash midstory may prevent germination and/or sufficient growth of baldcypress even during periods of extended drawdown. Ernst and Brooks (2003) note that Carolina ash and other species which reproduce and spread clonally have an advantage in heavily flooded forests.

Implications for Management

A handful of studies have shown baldcypress seedlings are capable of growing from 75 cm to over 1 m in height in their first year (see Neufield 1983, Conner 1995, Keeland and Conner 1999), depending on light, hydrologic conditions, soils, competition, and herbivory. Growth in light levels similar to those beneath a canopy is generally far less than this. In one study, light levels well above those found in the understory of this site (20% vs. 1-5%) led to a height increase of roughly 20 cm in the first growing season for newly germinated seedlings (Souther and Shaffer 2000). In most years, flood waters in the lowest parts of backswamp of the Broadneck Swamp reach 100 – 125 cm several times during the growing season, and usually remain at least 50-75 cm for several extended periods. This is likely what has prevented more widespread and regular

baldcypress and water tupelo regeneration across the floodplain. For example, assuming 2008's newly germinated seedlings grew 20 cm in their first 8 weeks (perhaps a liberal amount of growth in such conditions, but see Conner 1995), they would've been exposed to submergence for roughly 3 weeks in April. Floodwaters dropped below crown height for 2 days, and they would have subsequently been exposed to submergence for another 3½ weeks. This is assuming, of course, seedlings germinated at the height of the water level recorder, which is in an intermediate position of backswamp elevation.

To date, no research has examined differences in survival among submerged and non-submerged seedlings during the dormant season (Faulkner et al. 2009), which likely differ from submergence mortality rates during spring and summer. This could be important for managers attempting to simultaneously promote baldcypress regeneration, waterfowl habitat, and high flow levels for hydroelectric power generation. In order to utilize natural regeneration within the framework of a silvicultural system, there must first be the natural regeneration available. The general survey showed natural regeneration at the Broadneck Swamp exists at approximately 88 stems (<25 cm dbh)/ha, most of which was located in the slightly higher transition zones or elevated sites within the interior of the swamp.

This study demonstrates that, once available, advanced regeneration remains able to immediately respond favorably to release with sharply increased diameter growth and decreased mortality. Basal area growth rates of the largest released saplings are already on par with those of similar size having long grown in open conditions of an even-aged nature (McClurkin1965). If basal area growth continues to increase at observed rates, the largest saplings in treatment plots (those likely to eventually fully occupy the canopy) will grow at similar rates to present Broadneck adult baldcypress within 5 years, though the consistency of these rate increases remains at question. Results suggest that baldcypress can be managed in an uneven-aged regime if regular recruitment is

guaranteed and survival to sapling sizes is likely. Restoration of baldcypress in areas with compositionally or structurally altered canopies (including those damaged by hurricanes) can be restored if baldcypress advance regeneration exists.

An important question is: given limited finances and manpower, what is the optimum method of release to ensure survival and relatively rapid growth of baldcypress saplings into the canopy? It is clear that a positive correlation exists between initial size and raw sapling growth response to artificial canopy gap creation. This seems to favor targeting groups of larger (> 5 cm) saplings. Clusters of smaller saplings are more vigorous, with higher relative growth and a lower mortality rate, and their superior raw diameter growth dictates they may eventually "catch up" with larger saplings in the long run. However, the concern over larger saplings' high mortality seems to be nullified by increased survival in response to treatment, when otherwise a call for a triage situation in which saplings likely to die anyway be abandoned might be defensible. Indeed, it is the lower sub-canopy mortality rate of clusters of smaller saplings which potentially buys time for managers, enabling them to release groups with higher current mortality rates in the expectation that they will respond well, and clusters of smaller saplings will remain viable into the future when additional money, time, and/or manpower are available.

It may not be long before released saplings no longer increase growth rates year to year, as saplings found in natural gaps showed high but steady growth rates (by the 2nd year, artificially released saplings already showed similar rates to these potentially long-released individuals). The brevity of this study clearly warrants caution, as future monitoring may confirm such a plateau, a decline in growth rate increase, or a spike in mortality in response to floods or drought. However, given high sub-canopy sapling mortality rates, a lack of new cohorts of baldcypress seedlings available across the floodplain, and the continued regular extended growing season floods due to upstream

flow regulation, existing saplings should be released with haste if a significant increase in baldcypress composition in the Broadneck Swamp canopy is to be ensured.

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APPENDICES

APPENDIX A1:

Plot structural characteristics. Plots with red letters are treatment plots. Those with black are controls. Paired plots share a gray or white background color. At the bottom of each column are the mean, standard deviation, coefficient of variation, standard error, and 95% confidence interval for all plots combined.

Plot	# Saplings	# Saplings sub-sample	Dq (cm)**	Plot Cypress BA (m^2)*	Total Plot BA (m^2)	Non-baldcypress BA(m^2)
1A		26	2.90	0.123	3.21	3.084
1B		27	2.57	0.100	4.03	3.930
2A		25	3.27	0.150	3.37	3.220
2B		30	3.22	0.175	3.17	2.995
3A	91		3.70	0.098	2.87	2.772
3B	47		3.06	0.035	3.41	3.373
4A	66		4.88	0.124	3.71	3.582
4B	52		5.41	0.119	2.33	2.214
5A	87		5.68	0.220	2.49	2.268
5B	33		6.10	0.096	3.41	3.312
6A	27		1.72	0.006	3.07	3.061
6B	40		1.47	0.007	3.57	3.562
7A		20	9.88	1.092	3.35	2.253
7B	50		11.26	0.498	3.63	3.133
8A		16	7.58	0.515	3.08	2.567
8B	69		7.52	0.306	2.68	2.372
9A	85		6.26	0.262	2.65	2.386
9B	33		6.88	0.123	4.38	4.253
10A	85		6.75	0.304	2.65	2.344
10B	93		7.23	0.382	2.79	2.410
11A	60		2.44	0.028	4.09	4.058
11B	23		2.77	0.014	5.02	5.002
12A	59		7.26	0.244	2.31	2.066
12B	71		7.39	0.305	2.95	2.641
MEAN:	*87.3*		*5.30*	*0.222*	*3.26*	*3.036*
STDEV:	*55.6*		*2.607*	*0.235*	*0.66*	*0.752*
Coef of Var:	*63.74%*		*49.20%*	*105.92%*	*20.34%*	*24.77%*
ST Error:	*11.354*		*0.532*	*0.048*	*0.135*	*0.153*
95% CI:	*(65.0, 109.5)*		*(4.26, 6.34)*	*(.094 .316)*	*(2.99, 3.52)*	*(2.74, 3.34)*

APPENDIX A1 Note:

*On plots with sub-samples: Calculated by acquiring the average basal area/tree for sub-plot trees and then multiplying this by the predicted number of trees.

**On plots with sub-samples: This number represents the Dq (diameter of the tree with the average basal area) of only those baldcypress saplings sampled in sub-plots. Quadratic mean diameter is almost always greater than the arithmetic mean diameter, and becomes progressively larger than the arithmetic mean with increasing size and variance of the saplings.

APPENDIX A2:

Plot structural characteristics (continued) and plot growth data. Plots with red letters are treatment plots. Those with black are controls. Paired plots share a gray or white background color. At the bottom of each water tupelo basal area and water tupelo/baldcypress density columns are the mean, standard deviation, coefficient of variation, standard error, and 95% confidence interval for all plots combined. Basal area increment (BAI) is in cm^2 units. Diameter increment is in cm. Means and errors for growth data are reported in Chapter 3.

Plot	2009 Mean BAI	2010 Mean BAI	2009 Diam Inc	2010 Diam Inc	Tupelo BA (m^2)	No. Cyp/Tup Stems/ha
1A	3.869	5.488	0.552	0.725	3.08	636.0
1B	0.770	0.343	0.290	0.087	3.87	526.3
2A	3.098	4.334	0.599	0.574	3.20	504.4
2B	0.997	0.495	0.134	0.077	2.97	394.7
3A	2.280	4.271	0.336	0.569	2.76	307.0
3B	0.321	0.631	0.051	0.091	2.98	482.5
4A	2.133	3.982	0.282	0.463	3.58	372.8
4B	0.475	0.902	0.053	0.123	2.08	526.3
5A	2.977	5.011	0.306	0.461	2.22	350.9
5B	0.127	0.022	0.017	0.018	3.14	460.5
6A	1.534	2.2	0.474	0.575	3.05	350.9
6B	0.138	0.18	0.048	0.076	3.56	526.3
7A	5.852	9.05	0.283	0.462	2.23	350.9
7B	1.238	0.366	0.060	0.018	3.06	526.3
8A	2.590	5.125	0.167	0.296	2.50	394.7
8B	0.538	0.483	0.035	0.045	2.33	372.8
9A	2.036	5.019	0.191	0.45	2.11	307.0
9B	0.306	0.484	0.027	0.047	4.00	614.0
10A	2.269	5.44	0.179	0.452	2.24	394.7
10B	0.499	0.245	0.037	0.017	2.32	438.6
11A	1.588	1.978	0.389	0.474	4.05	592.1
11B	0.269	0.135	0.082	0.045	4.98	657.9
12A	1.549	4.366	0.115	0.328	1.97	219.3
12B	0.243	0.461	0.020	0.033	2.44	241.2
				MEAN:	2.95	439.51
				STDEV:	0.76	121.24
				Coef of Var:	25.91%	27.58%
				ST Error:	0.156	24.747
				95% CI:	(2.64, 3.25)	(391.0, 488.0)

APPENDIX B:

Sapling ages from slabs taken nearby canopy-gap plots. 22 of 24 plots were sampled; paired plots share similar colors, with control on the left and treatment on the right. Roman numerals denote ring counts from each of four sections. Slabs in red were thrown out for either too much sectional variation or for rings being too light. Sections with an "X" were not sampled because of problems with rotting in the section or very faint rings.

		Section								Section					
CONTROL	*DBH*	**I**	**II**	**III**	**IV**	**Median**	**Range**	**TREATMENT**	*DBH*	**I**	**II**	**III**	**IV**	**Median**	**Range**
2B1	*11.5*	25	34	38	33	**33**	13	12B1	*12.0*	27	25	X	X	**26**	2
2B2	*7.7*	29	33	32	31	**31**	4	12B2	*8.2*	24	23	26	25	**24**	3
2B3	*3.0*	15	15	15	15	**15**	0	12B3	*4.7*	24	24	24	23	**24**	1
3B1	*10.9*	16	14	14	14	**14**	2	15B1	*10.9*	23	24	24	24	**24**	1
3B2	*8.0*	17	17	17	17	**17**	0	15B2	*5.9*	24	24	25	24	**24**	1
3B3	*5.0*	15	15	16	16	**15**	1	15B3	*6.8*	21	21	21	22	**21**	0
4B1	*6.4*	15	16	15	15	**15**	1	5A1	*5.8*	20	19	20	20	**20**	1
4B2	*5.5*	17	17	17	17	**17**	0	5A2	*4.7*	12	12	12	12	**12**	0
4B3	*4.4*	15	15	15	X	**15**	3	5A3	*3.9*	19	17	17	18	**17**	2
5B1	*8.1*	16	15	16	18	**16**	3	3A1	*8.1*	16	16	16	16	**16**	0
5B2	*5.0*	14	15	17	15	**15**	3	3A2	*4.9*	14	14	14	X	**14**	0
5B3	*4.3*	13	13	13	13	**13**	0	3A3	*3.4*	13	13	13	13	**13**	0
6B1	*12.9*	20	19	19	20	**20**	1	6A1	*9.8*	13	13	12	13	**13**	1
6B2	*7.0*	12	12	12	12	**12**	0	6A2	*5.8*	14	14	14	14	**14**	0
6B3	*3.3*	15	15	X	16	**15**	1	6A3	*3.8*	13	12	12	X	**12**	1
7A1	*12.5*	31	30	33	30	**30**	2	9B1	*13.2*	29	24	26	26	**26**	5
7A2	*7.8*	24	25	23	24	**24**	2	9B2	*11.8*	22	22	22	22	**22**	0
7A3	*5.3*	23	24	23	26	**23**	3	9B3	*11.8*	22	22	20	18	**21**	4
7B1	*17.1*	26	25	31	29	**27**	6	9A1	*11.5*	27	23	24	28		5
7B2	*8.2*	31	28	28	25	**28**	3	9A2	*8.1*	26	22	25	28		6
7B3	*5.0*	25	25	25	23	**25**	2	9A3	*5.6*	25	26	26	X	**26**	1
11B1	*7.3*	15	17	18	17	**17**	3	11A1	*7.8*	20	20	20	X	**20**	0
11B2	*6.7*	21	22	23	21	**21**	2	11A2	*X*	X	X	X	X		
11B3	*4.0*	13	13	13	12	**13**	1	11A3	*4.0*	19	18	19	18	**18**	1
13A1	*12.0*	28	25	28	29	**28**	4	8A1	*11.7*	24	26	26	24	**25**	2
13A2	*8.6*	23	21	23	24	**23**	3	8A2	*8.0*	27	28	27	29	**27**	1
13A3	*4.7*	25	22	22	23	**22**	3	8A3	*5.8*	28	27	25	26	**26**	3
14A1	*12.2*	28	28	28	X	**28**	0	15A1	*9.1*	22	26	22	22	**22**	4
14A2	*8.2*	29	29	28	X	**29**	1	15A2	*13.3*	28	29	30	29	**29**	2
14A3	*5.4*	28	29	27	27	**27**	2	15A3	*4.4*	24	24	25	X	**24**	1
14B1	12.2	34	36	X	32	**34**	4	12A1	*12.8*	29	28	28	28	**28**	1
14B2	*9.9*	38	39	40	38	**38**	2	12A2	*7.2*	23	23	23	23	**23**	0
14B3	*5.1*	29	29	28	X	**29**	1	12A3	*4.0*	18	18	18	18	**18**	0

APPENDIX C:

Species encountered in canopy gap experiment plots and associated mean density, mean basal area, quadratic mean diameter, and importance value.

Species	Mean Density (stems/ha)	Basal Area (m^2/ha)	Dq (cm)	Importance Value
Nyssa aquatica	430.4	64.58	43.8	**44.39**
Taxodium distichum (all)	1896.9	5.35	6.2	**36.00**
Acer rubrum	10.1	0.29	20.3	**2.77**
Populus heterophylla	1.8	0.05	17.8	**0.76**
Fraxinus caroliniana	195.5	0.93	7.1	**11.22**
Liquidambar styraciflua	1.8	0.02	10.8	**0.75**
Ulmus americana	1.8	0.02	12.2	**0.75**
Quercus nigra	0.9	0.00	1.8	**0.37**
Betuala nigra	0.9	0.01	10.5	**0.37**
Quercus lyrata	1.8	0.00	3.1	**0.74**
Platanus occidentalis	3.7	0.03	15.4	**1.50**
Itea virginica	0.9	0.00	1.3	**0.37**
Taxodium distichum (> 25 cm)	*2.7*	*0.53*	49.6	*1.79*

Appendix D:

Leaf Area Index (PAI), diffuse non-interceptance (DIFN), and associated values for all treatment (red) and control (black) plots for 2008 and 2010. Paired plots share gray or white backing color. “SEL” is the standard error of PAI. “MTA” is the mean tilt angle, an approximation of leaf orientation relative to the horizon. “SEM” is the standard error of the mean tilt angle. The “predicted readings” is the number of readings that would be necessary given the calculated PAI and SEL to ensure (95% confidence interval) that the PAI is within +/- 10% of the calculated mean. Following treatment, which greatly enhanced canopy heterogeneity, the number of plots necessary shot up to well above the actual number used (15).

2008								2010						
Plot Num.	Date	PAI	SEL	Pred. Readings	DIFN	MTA	SEM	DATE	PAI	SEL	Pred. Readings	DIFN	MTA	SEM
1A	1-Aug	5.38	0.13	6.0	0.009	41	2	18-Aug	2.20	0.18	30+	0.228	63	1
1B	3-Aug	5.14	0.09	4.5	0.012	42	1	20-Aug	4.47	0.05	5	0.025	45	4
2A	4-Aug	5	0.15	8.0	0.015	44	4	19-Aug	2.09	0.16	30+	0.186	54	4
2B	3-Aug	4.8	0.09	4.5	0.016	42	3	20-Aug	4.80	0.09	11	0.018	43	2
3A	2-Aug	5.47	0.11	5.0	0.01	45	6	17-Aug	3.00	0.18	30+	0.173	72	6.9
3B	4-Aug	4.61	0.08	4.5	0.02	44	3	19-Aug	3.59	0.07	11	0.047	45	5
4A	8-Aug	5.12	0.14	7.0	0.013	43	3	23-Aug	2.97	0.09	20	0.194	60	4
4B	1-Aug	5.02	0.08	4.0	0.015	44	3	18-Aug	4.67	0.06	6	0.019	43	4
5A	8-Aug	5.45	0.08	4.0	0.009	42	2	23-Aug	3.08	0.08	16	0.211	55	6
5B	14-Aug	5.44	0.06	3.0	0.009	41	2	19-Aug	5.55	0.07	6	0.008	41	2
6A	6-Aug	4.41	0.09	5.0	0.025	44	3	22-Aug	2.33	0.10	30+	0.264	88	15
6B	6-Aug	4.83	0.06	3.5	0.016	43	3	22-Aug	4.20	0.06	8	0.028	44	5
7A	11-Aug	5.65	0.04	2.5	0.008	42	2	19-Aug	3.85	0.13	25	0.061	54	4
7B	12-Aug	5.31	0.06	3.0	0.01	41	1	19-Aug	5.21	0.06	6	0.012	42	2
8A	11-Aug	5.95	0.06	3.0	0.006	42	2	19-Aug	3.52	0.12	25	0.09	60	6
8B	12-Aug	5	0.1	5.0	0.013	41	1	18-Aug	4.77	0.10	12	0.017	42	3
9A	2-Aug	6.26	0.1	4.0	0.005	44	6	17-Aug	3.21	0.12	28	0.128	65	3.3
9B	14-Aug	5.27	0.05	3.0	0.011	43	3	18-Aug	4.49	0.03	4	0.022	44	5
10A	10-Aug	5.49	0.05	3.0	0.008	40	2	20-Aug	3.25	0.11	25	0.117	63	3
10B	9-Aug	5.4	0.08	4.0	0.01	42	2	19-Aug	5.45	0.11	11	0.01	41	1
11A	7-Aug	4.72	0.03	2.0	0.016	41	3	21-Aug	2.38	0.09	29	0.252	76	12
11B	7-Aug	4.72	0.04	2.5	0.017	42	3	21-Aug	4.34	0.03	4	0.024	42	3
12A	9-Aug	5.33	0.09	4.5	0.012	45	4	19-Aug	3.22	0.19	30+	0.119	64	4
12B	10-Aug	5.44	0.03	2.0	0.009	41	3	20-Aug	5.15	0.03	3	0.013	45	5

APPENDIX E:

Number of saplings in each plot in 2008, 2009, and 2010 and mortality rates for 2008, 2009, and both years combined. Paired plots share gray or white background color. Means and errors by treatment type and year are reported in Table 3-7.

Plot	2008	2009	2010	Treatment Type	'08-'09 Plot Mort	'09-'10 Plot Mort	2-Yr Total Plot Mort	Initial Dq (cm)
1A	26	26	25	Treated	0.00%	3.85%	1.94%	2.90
1B	27	27	27	Control	0.00%	0.00%	0.00%	2.57
2A	25	25	25	Treated	0.00%	0.00%	0.00%	3.27
2B	30	25	24	Control	16.67%	4.00%	10.56%	3.22
3A	89	82	82	Treated	7.87%	0.00%	4.01%	3.70
3B	47	47	47	Control	0.00%	0.00%	0.00%	3.06
4A	66	62	61	Treated	6.06%	1.61%	3.86%	4.88
4B	53	49	48	Control	7.55%	2.04%	4.83%	5.41
5A	87	79	77	Treated	9.20%	2.53%	5.92%	5.68
5B	34	31	27	Control	8.82%	12.90%	10.89%	6.10
6A	24	23	21	Treated	4.17%	8.70%	6.46%	1.72
6B	40	39	39	Control	2.50%	0.00%	1.26%	1.47
7A	22	17	17	Treated	22.73%	0.00%	12.10%	9.88
7B	50	43	33	Control	14.00%	23.26%	18.76%	11.26
8A	17	12	12	Treated	29.41%	0.00%	15.98%	7.58
8B	70	64	53	Control	8.57%	17.19%	12.99%	7.52
9A	83	76	75	Treated	8.43%	1.32%	4.94%	6.26
9B	33	30	29	Control	9.09%	3.33%	6.26%	6.88
10A	84	73	72	Treated	13.10%	1.37%	7.42%	6.75
10B	93	84	72	Control	9.68%	14.29%	12.01%	7.23
11A	58	55	52	Treated	5.17%	5.45%	5.31%	2.44
11B	23	22	21	Control	4.35%	4.55%	4.45%	2.77
12A	58	43	41	Treated	25.86%	4.65%	15.92%	7.26
12B	71	52	41	Control	26.76%	21.15%	24.01%	7.39
Totals:	1139	1034	980					
		Overall Two-Year Mortality:	13.96%					
		Overall Per-Year Mortality:	7.24%					